

Introducing Unsaturated Soil Mechanics to Undergraduate Students through the Net
Stress Concepts

By

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ABSTRACT

The purpose of this research was to introduce unsaturated soil mechanics to the undergraduate geotechnical engineering course in a concise and easy to understand manner. Also, it was essential to develop unsaturated soil mechanics teaching material that merges smoothly into current undergraduate curriculum and with sufficient flexibility for broad adaptation by faculty. The learning material consists of three lecture modules and a laboratory module.

The lecture modules introduced soil mechanics for the general 3-phase medium condition with the saturated soil as a special case. The three lecture modules that were developed are (1) the stress state variables for unsaturated soils, (2) soil-water characteristic curves, and (3) axis translation. A PowerPoint presentation was created to present each module in an easy to understand manner so that the students will enjoy the learning material.

Along with the lecture modules, a laboratory module was developed that reinforced the key aspects and concepts for unsaturated soil behavior. A laboratory manual was created for the Tempe Pressure Cell and Fredlund SWC-150 device (one-dimensional oedometer pressure plate device) in order to give the instructor and institution a choice of which testing equipment best fits their program. Along with the laboratory manuals, an analysis guide was created to help students with constructing SWCCs from their laboratory.

A soil type recommendation was also researched for use in the laboratory module. The soil ensured acceptably short equilibrium times along with a wide range of suction

values controllable by both testing equipment (Tempe Pressure Cell and Fredlund SWC-150). A silt type soil material was recommended for the laboratory module.

As a part of this research, a smooth transition from unsaturated to saturated condition was demonstrated through laboratory volume change experiments using a silt soil tested in an oedometer-type pressure plate device. Three different experiments were conducted: (1) volume change for unsaturated soils in response to suction and net normal stress change, (2) volume change for saturated soils in response to effective stress change, as determined using unsaturated soils testing equipment, and (3) traditional consolidation tests on saturated soil using a conventional consolidometer device.

DEDICATION

This thesis is dedicated to my mom Carlily Ojeda, who provided both emotional and financial support in my academic career. She has sacrificed a great deal and supported me to get my education and there are no words to thank her enough.

I would also thank my wife and best friend, Lisette Ramirez, for her inspiration and cheering me through my academic career. Thank you for sacrificing so much in order to allow me to finish my education.

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CHAPTER 1

1 INTRODUCTION

1.1 Objective

The purpose of this study was the development of methods for teaching unsaturated soil mechanics to undergraduates based on the net stress concepts that provided an ease of transition from saturated to unsaturated soil conditions. The instructional material focused on the smooth merger of unsaturated soil theory with traditional saturated soil mechanics theory. In development of teaching modules, a sub-objective was undertaken: development of a laboratory module demonstrating the role of soil suction as a stress state variable in unsaturated soil behavior, which required identification of soil type that exhibits acceptable equilibration times for the unsaturated soils volume change testing while also exhibiting the traditional s-shaped consolidation curve for saturated soil consolidation testing. The laboratory testing performed in the development of the teaching modules also represented a unique data set wherein a given soil was tested for volume change response over a range from dry to saturated moisture conditions.

1.2 Background

Unsaturated soils associated with expansive soils have been a major concern in the United States. About \$15 billion in damages every year is reported in the United States. John and Holtz (1973) indicated that each year expansive soils have caused major damages to houses, buildings, roads and pipelines, more than all of the natural disasters combined. The damage to structures caused by expansive soils have increased every year. Arid climates are more prone to shrinkage and swelling of soil so it has been a major

concern in those regions. There has been an increase of awareness of this problem therefore; there has been some growth incorporating unsaturated soil mechanics into engineering practice.

There has been very little movement towards incorporating unsaturated soil mechanics into the undergraduate geotechnical engineering curriculum. There is very little or no unsaturated soil mechanics material being taught in these courses. Traditional textbooks being used in the undergraduate geotechnical engineering class focus on saturated soil mechanics, with unsaturated soils cases generally being presented from a total stress perspective only. Some universities offer a course in unsaturated soil mechanics at the graduate level but students who select these courses have very little background knowledge in the subject. It has been a challenge for the industry to use unsaturated soil principles in practice because students are graduating with very little understanding in unsaturated soil principles.

Unsaturated soil mechanics has lagged behind saturated soil mechanics for a variety of reasons. One of the main reasons is that the development and understanding of soil mechanics for unsaturated soils has been very difficult due to the experimental and theoretical complexities of the subject. According to Fredlund, Fredlund, & Rahardjo, 2010, the 1980-decade was a period when boundary value problems were solved using numerical, finite element and finite difference modeling methods. Computers were needed to solve these complex numerical problems. With the increase in innovation of computers, there has been a rapid resurgence in the advancement of unsaturated soil mechanics.

Including a few lecture modules into the undergraduate geotechnical engineering curriculum has been a major step in the right direction for exposure of unsaturated soil mechanics. The lecture modules lay down the foundation of unsaturated soil principles for the graduate level course in unsaturated soil mechanics. Implementation of the material into the curriculum by universities across the United States was a challenge to accomplish. Working with partner institutions was a crucial step in beginning the process for implementation.

1.3 Scope of Work

The scope of this study was the development of unsaturated soil mechanics lectures and laboratory modules for implementation into the undergraduate geotechnical engineering curriculum. The lecture modules were created in a way for students to understand the learning material very easily and to grasp on the common concepts of unsaturated soil mechanics. Three lecture modules were created including one being a pre-lecture to the laboratory module. The three lecture modules covered (1) stress state variables, (2) soil-water characteristic curves (SWCC), and (3) axis translation technique to obtain SWCC of a soil (pre-lecture to the laboratory module). Along with the lecture modules, the laboratory module was also developed. Laboratory manuals were created for the Tempe-Cell and SWC-150 (1-D oedometer pressure plate device) to allow the students to follow and understand the directions more easily while conducting the experiments.

Working with a certain soil type for the laboratory module was important for students to achieve quality results within acceptable equilibrium times for unsaturated soils. Part of this study was to determine which soil type works best to acquire these

conditions. Certain soil properties such as liquid limit, plasticity index, pore-size distribution, and maximum density were recommended for the soil type used for the laboratory module.

The final scope of this study was to demonstrate a transition from saturated to unsaturated soil conditions through volume change measurements. A SWCC test with volume change measurements was performed using an oedometer-type pressure plate device. A traditional consolidation test was performed on the same oedometer-type pressure plate device. A traditional one-dimensional consolidation test for the saturated condition was also performed and compared to the test results obtained from the consolidation test using the oedometer-type pressure plate device. A discussion was followed to describe the transition from unsaturated to saturated soil condition.

1.4 Organization

This thesis was organized into the following six chapters including the introductory chapter that discusses the purpose of this study along with a brief background and overview of the research conducted. Chapter 2 presents the literature review to provide background information that is relevant to the following chapters of the dissertation. Chapter 3 is the development of the lecture modules and the learning materials what should be included for unsaturated soil mechanics. Chapter 4 is the development of the laboratory module and the analysis in the soil type determination. Chapter 5 consists of the integration of measure volume change for saturated and unsaturated soils. Chapter 6 discusses what implementation efforts are still needed to teach unsaturated soil mechanics at the undergraduate level.

CHAPTER 2

2 LITERATURE REVIEW

2.1 Introduction

The development of the learning materials acquired contain, (1) assurance of fit with traditional introductory geotechnical course curriculum, including in particular a smooth transition between saturated and unsaturated soil mechanics concepts, (2) development of easy to understand materials on the importance of two independent stress state variables for unsaturated soil conditions, and (3) controlled the volume of learning materials to a level that would be readily acceptable by a large number of geotechnical engineering faculty, which required development of materials that could be substituted for some traditional lectures and minimization of added material. Also, the best suitable soil was determined for students to use in the laboratory module which is key for simple and time-appropriate equilibration times to conduct the laboratory tests. The history of unsaturated soil mechanics and development of the basics theories and principles are used in the development of learning materials to introduce unsaturated soil mechanics to undergraduate students or to other engineers that are not familiar with this subject are discussed in this chapter. Also, a review of soil volume change theory is provided for saturated and unsaturated soil conditions, with emphasis on the role of stress state variables.

2.2 Three-Phase System for Unsaturated Soils

Unsaturated soil is generally discussed as a three-phase system composed of soil solids, water, and air. The relative distribution of these three components are important to understand the properties of the soil, primarily because the nature of the air – water

interface is controlled by the distribution of these three components. An element of unsaturated soil is idealized in Figure 2.1. The soil solids, or the solid phase, consist of soil particles such as sand, silt, and clay. The soil is occupied by air voids, which may be completely or partially filled with water. The water that occupies these air voids is the water phase. The air filled voids constitutes the air phase of the three-phase soil system.

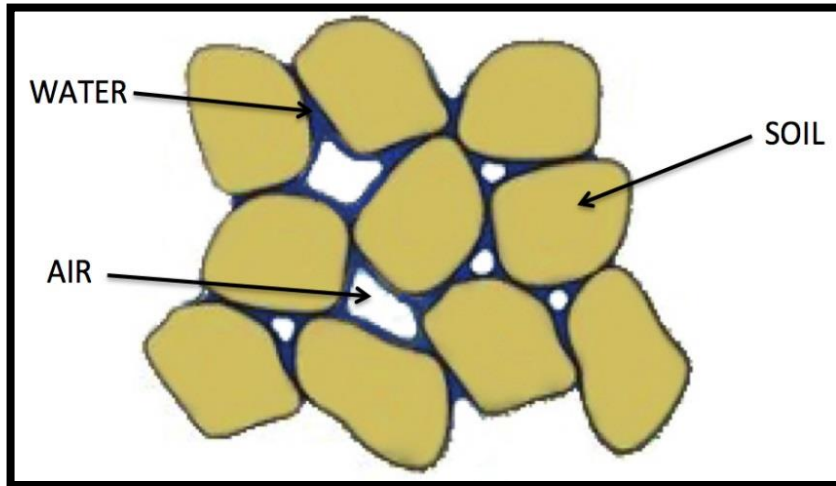


Figure 2.1 Element of Unsaturated Soil

Fredlund and Morgenstern (1977) introduced a fourth phase called the contractile skin, which is the same as the water-air interface. The water-air interface is compared to as a thin membrane interwoven throughout the voids of the soil, forming a partition between the air and water phases (Fredlund, Fredlund, & Rahardjo, 2012). The air–water interface is sometimes considered as a fourth phase because this interface affects volume change and shear strength. Because the air- water interface is directly linked to the air, water, and solid phases, unsaturated soil is most simply represented as a three-phase system.

The soil is considered to be saturated when all the void space is filled with water. Saturated soil is a special case of the three-phase system since all the void space is filled with water and no air is present. The system converts into a more general form, which only consists of only solids and water. Due to no air being present, a saturated soil can be viewed as a two-phase system. Figure 2.2 displays an element of saturated soil of the more general form of the three-phase system.

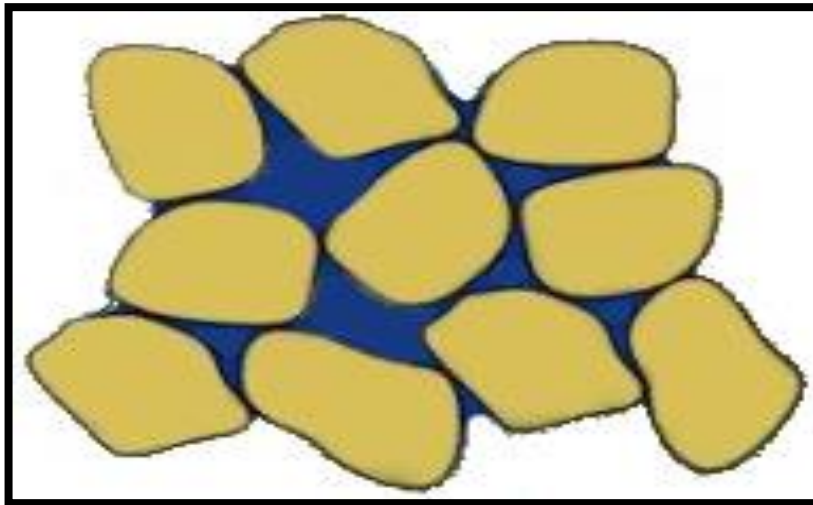


Figure 2.2 An Element of Saturated Soil

2.3 Stress State Variables for Unsaturated Soil

The most commonly used stress state variable to describe the physical behavior of saturated soils is the effective stress variable. The effective stress variable is applicable to sands, silts, or clays and is independent of the soil properties. The effective stress variable controls the volume change process and shear strength of a saturated soil. The effective stress is expressed in the form of an equation:

$$\sigma' = \sigma - u_w \dots\dots\dots (2.1)$$

Where:

σ' = Effective normal stress

σ = Total normal stress

u_w = Pore-water pressure

It can be independently applied to each of the three Cartesian coordinate directions at a point in a continuous medium therefore; the effective stress takes on the form of a stress tensor in a 3 x 3 matrix. Terzaghi (1936) defines the effective stress of a saturated soil in terms in a 3 x 3 matrix:

$$\sigma' = \begin{bmatrix} (\sigma_x - u_w) & \tau_{yx} & \tau_{zx} \\ \tau_{xy} & (\sigma_y - u_w) & \tau_{zy} \\ \tau_{xz} & \tau_{yz} & (\sigma_z - u_w) \end{bmatrix} \dots\dots\dots (2.2)$$

Where:

σ' = Effective normal stress

$\sigma_x, \sigma_y, \sigma_z$ = Total normal stress in the x, y, and z directions, respectively.

The effective stress variable defines the stress state of saturated soils and governs all mechanical behavior. A change in the effective stress due to a change in the total normal stress or a change in the pore-water pressure changes the equilibrium state of a saturated soil, and causes volume change. For this reason, the effective stress is qualified as a stress state variable for saturated soils. The effective stress equation for saturated soils cannot be used with unsaturated soils due to the fact that the soil is not 100% saturated and the resulting presence of air in the voids.

In 1977, Fredlund and Morgenstern used the concept of multiphase continuum mechanics to write the equilibrium equations for unsaturated soils. Fredlund and Morgenstern analysis concluded that any two of the three possible stress state variables

can be used to define the stress state of an unsaturated soil (Fredlund, Fredlund, & Rahardjo, 2012). The three possible combinations of stress state variables for unsaturated soils are:

1. $(\sigma - u_a)$ and $(u_a - u_w)$
2. $(\sigma - u_w)$ and $(u_a - u_w)$
3. $(\sigma - u_a)$ and $(\sigma - u_w)$

The stress states variable combinations that are widely accepted in formulating unsaturated soil mechanics problems are the net normal stress $(\sigma - u_a)$ and matric suction, $(u_a - u_w)$. This combination is chosen to be the best suitable stress state variables due to the following:

1. Stress state variables can be experimentally tested in the laboratory
2. Stress state variables that can be theoretically justified using equilibrium considerations.
3. Stress state variables where the component stresses can be measured in engineering practice
4. Stress state variables that meet the definition of state variables in continuum mechanics.

For unsaturated soils, effects of external total stresses and internal pore-water pressure must be considered. To evaluate the stress state of an unsaturated soil, there needs to be two independent stress state variables. The stress state variables for unsaturated soil take on the form of two independent stress tensors when considering the

state of stress at a point in three dimensions. The two independent stress tensors for unsaturated soil are as follows (Fredlund, D., 1997b):

$$\begin{bmatrix} (\sigma_x - u_a) & \tau_{yx} & \tau_{zx} \\ \tau_{xy} & (\sigma_y - u_a) & \tau_{zy} \\ \tau_{xz} & \tau_{yz} & (\sigma_z - u_a) \end{bmatrix} \dots\dots\dots (2.3)$$

$$\begin{bmatrix} (u_a - u_w) & 0 & 0 \\ 0 & (u_a - u_w) & 0 \\ 0 & 0 & (u_a - u_w) \end{bmatrix} \dots\dots\dots (2.4)$$

These two independent stress tensors containing the net normal stress (Eqn. 2.3) and matric suction (Eqn. 2.4) along with the shear stresses form the basis for the development of unsaturated soil mechanics.

There have been a numerous attempts to determine a single effective stress variable to define the stress state of an unsaturated soil. Equation (2.5) proposed by Bishop in 1959 is the oldest and most referenced single-valued effective stress equation for unsaturated soils.

$$\sigma' = (\sigma - u_a) + \chi(u_a - u_w) \dots\dots\dots (2.5)$$

Where:

$(\sigma - u_a)$ = Net normal stress

$(u_a - u_w)$ = Matric suction

χ = Soil parameter related to degree of saturation and range from 0 to 1

Bishop's equation relates net normal stress to matric suction through incorporation of a single-valued soil property, χ . The Bishop's equation should not be referred to as a fundamental description of stress state for an unsaturated soil because the equation contains a soil property and should be referred to as a constitutive equation

(Fredlund, Fredlund, & Rahardjo, 2012). In addition, there were difficulties in determining the parameter, χ .

Jennings and Burland (1962) examined the behavior of some partially saturated soils in relation to validity of Bishop's equation (Zapata et al., 1999). They determined that the parameter χ does not apply to the effective stress theory when the degree of saturation is below a critical degree of saturation for a certain soil type. The critical degree of saturation for sands is about 50% while clays appear to have a critical degree of saturation as high as 90%. The two authors presented that it was not the effective stress that controls the behavior of partially saturated soils based on the experiments they conducted.

When an unsaturated soil becomes wetted, the degree of saturation increases and eventually approaches 100%. When the soil goes from unsaturated to saturated condition, the pore-water pressure, u_w , approaches the pore-air pressure, u_a , and the matric suction, $(u_a - u_w)$, goes towards zero. The second tensor, the soil suction tensor, effectively disappears as the pore-water pressure becomes equal to pore-air pressure and the first tensor is left to represent the stress state of saturated soil. When the matric suction becomes zero, the pore-air pressure in the first tensor is replaced with the pore-water pressure since the pore-water pressure is equal to the pore-air pressure. In summary, when unsaturated soil becomes fully saturated, the pore-water pressure equals to the pore-air pressure and the second tensor disappears and is left with one stress tensor for saturated soil (Eqn. 2.2) which provides a smooth transition from unsaturated to saturated condition.

2.4 Soil-Water Characteristics Curves for Unsaturated Soils

The soil-water characteristic curve, SWCC, is used to describe the relationship between the amount of water in the soil and matric suction. It is also known as the water retention curve but the term soil-water characteristic curve is more widely used in geotechnical engineering. This relationship is normally plotted as the variation of gravimetric water content, w , volumetric water content, θ , or degree of saturation, S , with respect to matric suction. The SWCC is of particular importance in unsaturated soil mechanics because it relates some measure of soil water content to one of the controlling stress state variables, matric suction. The SWCC was first developed by soil science therefore, the volumetric water content was commonly used as the soil water content measure, and no emphasis was placed on soil volume change in response to change in soil suction or on impacts net normal stress.

Figure 2.3 shows a typical soil-water characteristic curve. A SWCC has three distinct zones of desaturation boundary effect, transition, and residual zones. The unsaturated soil properties in the transition zone become nonlinear, and as a result, subsequent mathematical formulations are nonlinear (Fredlund, Fredlund, & Rahardjo, 2012). On the SWCC, there are two key transition points and they are the air-entry value (AEV) and the residual value condition. The air-entry value is defined as the matric suction value must be exceeded before air enters the voids of the soil as it is being dried from a saturated state. The residual condition is the residual volumetric water content at which in increase in matric suction does not produce a change in water content.

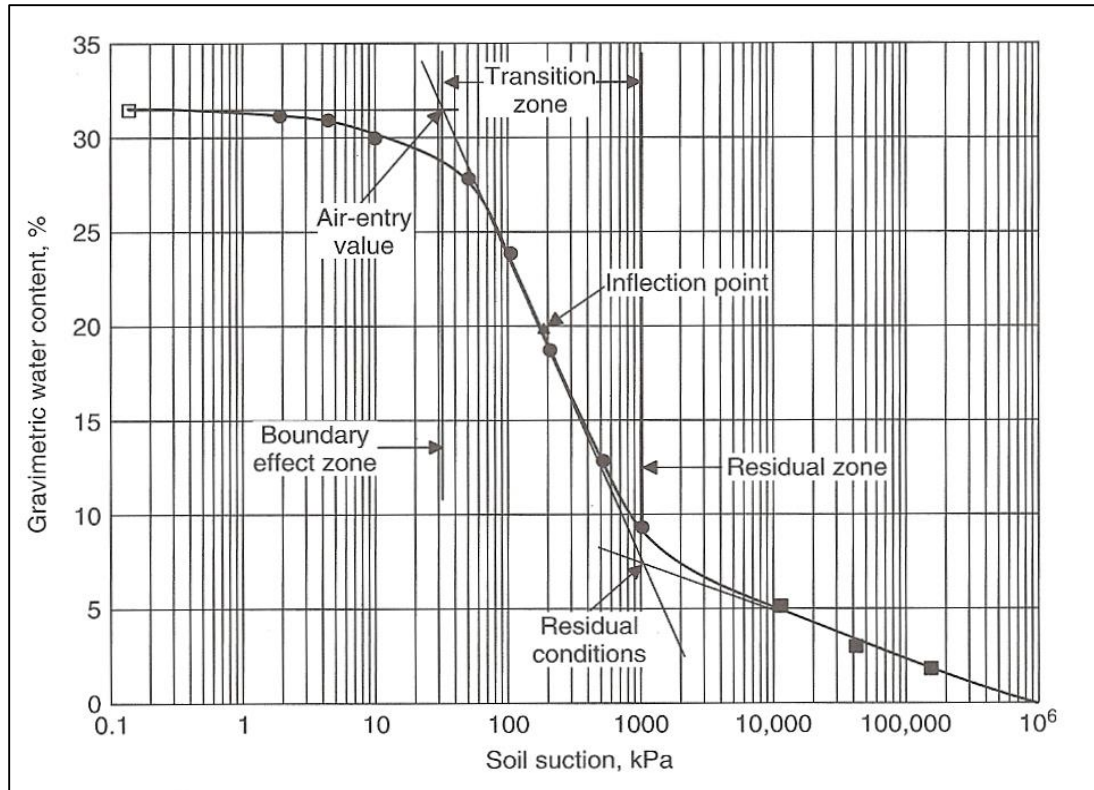


Figure 2.3 Typical SWCC (Fredlund, Fredlund, & Rahardjo, 2012)

Unsaturated soil property functions are estimated using the SWCC and the saturated soil properties. The SWCC becomes the single most valuable piece of soil information for geotechnical engineering practice involving unsaturated soils (Fredlund, Fredlund, & Rahardjo, 2012). It is important that the SWCC is properly estimated or measured and interpreted to obtain the best possible results in unsaturated soil mechanics problems. Constructing a SWCC requires a lot of time and several tests to obtain all the necessary information. In order to facilitate this problem, several mathematical models have been developed to obtain a SWCC for a particular soil from just a few data point such as the Van Genuchten (1980), Fredlund and Xing (1994), and Pereira and Fredlund (2000) equations.

2.5 Deformation State Variables

Deformation state variables describe the volume change of unsaturated soils.

Unsaturated soils are a three-phase system consequently; the deformation variables are required to describe the changes in each phase in an element derived from the continuity requirement for a multi-phase continuum (Fredlund 1973a, 1974). The total volume change of a soil element must be equal to the sum of the volume changes associated with each phase. The total volume change can also be called the volumetric strain. The volumetric strain is the change in the volume of the voids to the initial overall volume of the soil element. The total volume change for an unsaturated soil is stated assuming the soil particles are incompressible:

$$\epsilon_v = \frac{\Delta V_v}{V_o} = \frac{\Delta V_w}{V_o} + \frac{\Delta V_a}{V_o} \dots\dots\dots (2.6)$$

Where:

ϵ_v = Volumetric strain

V_o = Initial overall volume of unsaturated soil element

V_v = Volume of soil voids

V_w = Volume of water

V_a = Volume of air

The volumetric strain is the sum of normal strain components in the x, y, and z directions on a Cartesian coordinate system. Equation (2.6) describes the change in the overall soil element volume.

A change in volume of a soil element is commonly induced by added net normal stress, which is associated with soil compression. The change in void ratio (the ratio of

volume of voids to the volume of soil solids), e , describes the volumetric deformation for saturated soil and is given in the following constitutive equation:

$$de = a_v d(\sigma - u_a) \dots\dots\dots (2.7)$$

Where:

a_v = Coefficient of compressibility

A one-dimensional compression or consolidation test is performed to obtain a plot showing the relationship between void ratio and effective stress for a saturated soil. A typical void ratio vs. log-effective stress curve is shown in Figure 2.4. This relationship is used to estimate the settlement of a compressible soil layer due to a change in effective stress or saturated soil conditions. The coefficient of compressibility is the slope of the compression curve when the results from the consolidation test are plotted.

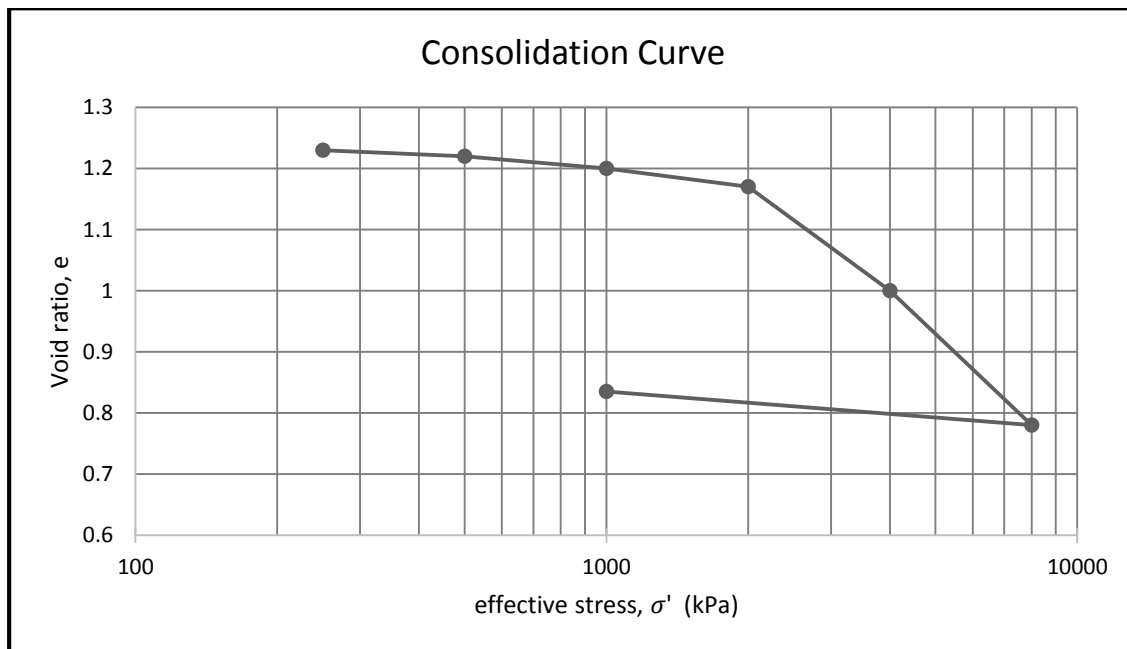


Figure 2.4 Typical Consolidation Curve

Void ratio can also be used to describe the deformation state for unsaturated soil.

Using soil mechanics terminology, the change in void ratio of an unsaturated soil under a three-dimensional loading can be written as (Fredlund, Fredlund, & Rahardjo, 2012):

$$de = a_t d(\sigma - u_a) + a_m d(u_a - u_w) \dots\dots\dots (2.8)$$

Where:

de = Change in void ratio

a_t = Coefficient of compressibility with respect to a change in net normal stress

a_m = Coefficient of compressibility with respect to a change in matric suction

A one-dimensional compression or consolidation test is performed to plot two different independent relationships between (1) void ratio and net normal stress and (2) void ratio and matric suction to estimate the settlement of a compressible layer. The coefficient of compressibility with respect to a change in net normal stress is the slope of the compression curve when the results from the consolidation test are plotted void ratio vs. net normal stress. The coefficient of compressibility with respect to a change in matric suction is the slope of the compression curve when the results from the consolidation test are plotted void ratio vs. matric suction. Figure 2.5 shows the constitutive surface for an unsaturated soil. This figure is a three-dimensional plot because two stress state variables, net normal stress and matric suction, are required to define the three-phase system of an unsaturated soil. The figure also shows a two-dimensional plot for the stress state variable vs. void ratio to determine the coefficient of compressibility with respect to the stress state variable.

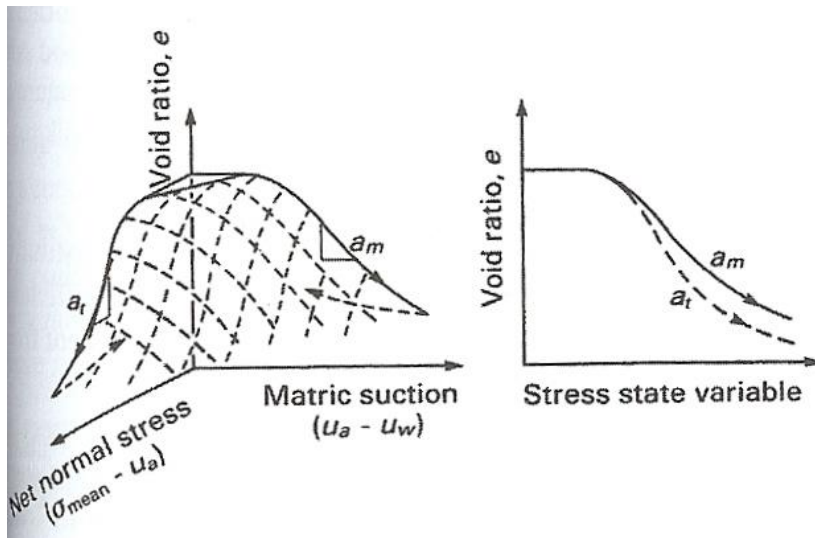


Figure 2.5 Void Ratio Constitutive Surface for an Unsaturated Soil (Fredlund, Fredlund, & Rahardjo, 2012)

The net normal stress-void ratio plane for an unsaturated soil is the same plot for a saturated void ratio-effective stress plot. Remember, when an unsaturated soil approaches 100% saturation, matric suction becomes zero and the net normal stress becomes the effective stress. Therefore, the net normal stress-void ratio plane is the same as the two-dimensional plot for the saturated condition. This is only valid when the unsaturated soil element becomes fully saturation.

2.6 Test Equipment for Volume Change Response

Testing on either saturated or unsaturated soils is needed to estimate the one-dimensional volume change of a soil. The soil can either swell or compress at a given stress applied to it. A consolidometer is typically used to determine the volume change for the saturated condition of a soil. Whereas for unsaturated soils, a one-dimensional oedometer pressure plate with matric suction change capabilities is used.

To simulate a one-dimensional compression in the laboratory for a saturated soil, the soil is compressed in a device called a consolidometer (Figure 2.6), which is sometimes called a one-dimensional oedometer (Holtz, Kovacs, and Sheahan, 2011). A soil sample or specimen is placed into a confining ring and placed on the base of the consolidometer. One porous stone is placed at the bottom of the soil specimen and one at the top. The porous stone will allow the water to drain out of the soil specimen during the consolidation process. The soil specimen is then saturated with water. Once the specimen is saturated with water, a load is applied to the upper porous stone. The soil can either compress or swell during the loading process. If the stress is below the swell pressure (stress level where swell or compression will not occur) of the soil, then the soil will swell but if the stress is higher than the swell pressure, then the soil will compress. During the consolidation process, deformations reading are taken with a dial gage with respect to time to determine the relationship between load and deformation. Once the soil specimen is consolidated and comes to equilibrium, the process is repeated by doubling the previous load increment until there are sufficient data points to construct a consolidation curve. A detail test procedure is covered by ASTM D2435 test standard for one-dimensional consolidation.

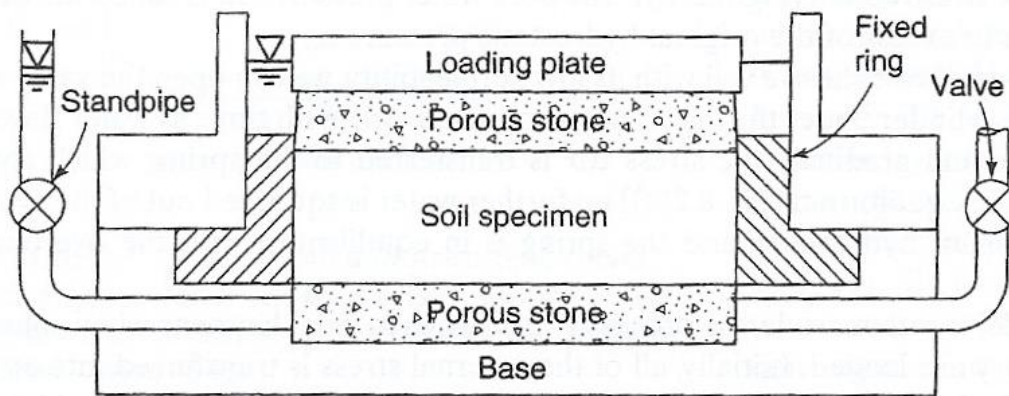


Figure 2.6 Fixed-Ring Consolidometer Cross-Section (Holtz, Kovacs, and Sheahan, 2011)

A one-dimensional oedometer pressure plate device with matric suction capabilities is used for unsaturated soils. The main difference between this device and a consolidometer is the soil suction application. Matric suction is one of the factors in determining the volume change for an unsaturated soil. Therefore, a device needs to be able to apply a net normal stress and matric suction to an unsaturated soil. The one-dimensional oedometer pressure plate device is also used in constructing an SWCC of a soil because water content readings can be measured at different matric suction values. A device such as the SWC-150 (Fredlund SWCC device) is a simple unsaturated soil testing apparatus that is capable of applying matric suctions at various applied total stress. This device is capable to apply up to 1500 kPa of soil suction and up to 2,000 kN maximum load.

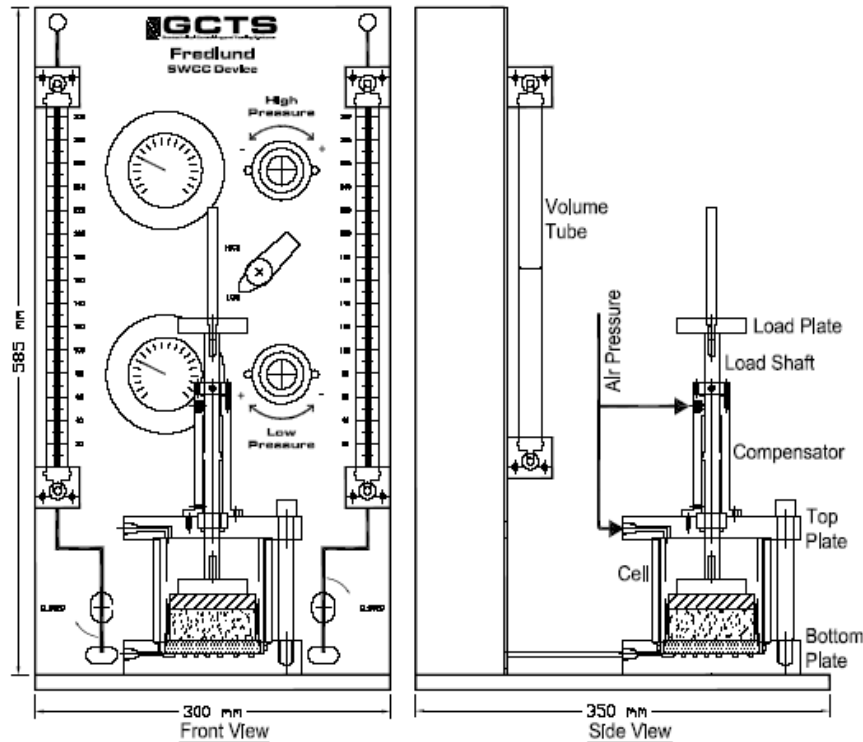


Figure 2.7 GCTS Pressure Plate Device (Courtesy of GCTS, Tempe, AZ)

The procedure to use a pressure plate device is a little more complex. A soil sample is placed in a confining ring and then saturated with water. Once the soil specimen is saturated, it is placed inside cell and a porous stone is placed on top of the specimen before applying the top plate. The volume tubes are then filled with water and a flushing device is used to remove any trapped air in the base of the cell. Once all the air is removed, a target pressure (matric suction) and load is applied to the soil specimen. Let the system equilibrate and take water volume change and deformation readings with time. The test may take several days for the system to equilibrate. Once the system is at equilibrium, the next pressure or load increment is applied to the soil specimen and the process is repeated. A detailed procedure is supplied from the manufacturer of each pressure plate device

Chapter 3

3 DEVELOPMENT OF LECTURE MODULES

3.1 Introduction

The purpose of the development of the lecture modules on unsaturated soil mechanics is to have the instructors of the undergraduate geotechnical engineering classes incorporate the material into their current curriculum. The modules include the basic and important concepts of unsaturated soil principles that the students should know and comprehend.

The first and most important module that needs to be developed and implemented is the stress state variables module for unsaturated soils. Identifying the stress states of an unsaturated soil is the first step in estimating the shear strength and compressibility of the soil. This is important for students to understand because it is the platform for unsaturated soil applications.

The soil-water characteristic curve (SWCC) lecture module is the second module that is developed. This is the second lecture to be presented since it consists of a relationship between matric suction (one of two stress state variables) and water content measurement at different net normal stresses (second of the two stress state variables). This relationship is used to develop other important unsaturated soil relationships such as the hydraulic conductivity, the shear strength and the compressibility functions.

The axis-translation lecture module is to be presented last and it is considered to be a pre-lab lecture for the laboratory module. This module includes how and why the axis-translation method is used in the measurement of soil matric suction. Some of the

soil-water characteristic curve lecture will be reiterated since the purpose of using the axis-translation technique is to construct the SWCC of the soil of interest.

3.2 Stress State Variables Module

For many geotechnical engineering applications it is necessary to identify measureable stress variables that control the soil's deformation and shear strength. In soil mechanics, the soil is considered to be a continuous medium. The macro-level approach, where the soil is treated as a continuous medium, is the approach taken in the development of the stress state variables lecture module. In this module, it is recommended that soil properties are determined at the macro-level, even though it is helpful from time to time to understand what is happening at the micro level.

3.2.1 Soil Phases

A soil is generally a three-phase medium that consists of solid soil particles, water, and air. In order to represent the three phases, phase relationships are obtained, which produce weight-mass volume relationships for unsaturated soils. Volumetric water content and degree of saturation (preferably degree of saturation for geotechnical engineering applications) is of particular interest for unsaturated soil studies. A soil is unsaturated when both air and water occupy the void spaces between the soil particles. Air voids are essentially all inter-connected when the degree of saturation is below about 85%. Unsaturated soils differ from saturated soil as water is the only occupant of the void spaces in the saturated soil condition and consequently, saturated soils have a degree of saturation of 100%.

Stress is defined as the force per unit area. In soil mechanics, traditionally the gross cross-sectional area is used in defining stress, which means the unit area represents a plane that cuts across the solid soil particles, void spaces and anything inside the void spaces. In using the gross cross-sectional area as the unit area, the soil is being treated as a continuous medium. This is also referred to as taking a macro-level continuum mechanics approach to identify measureable stress quantities and soil properties that are necessary for many geotechnical-engineering applications. Practicing engineers have chosen to accept the macro-level approach since it is consistent with continuum mechanics principles used in other engineering applications and stand actually easier to apply to practice than the micro-level approach given the numerous challenges faced when characterizing micro-level behavior.

3.2.2 State of Stress for Unsaturated Soil

There are two different types of forces that act on the soil, external and internal forces. External forces consist of the weight of the soil itself and loads applied by structures. These external forces when distributed over a cross-sectional area are called total stresses. The pore-water pressure and pore-air pressure constitute the internal forces which can be either negative or positive.

With soil being a three-phase medium (solid, water and air), there are three stresses that must be considered in describing the overall state of soil stress: (1) total normal stress, which is generally compressive; (2) pore-air pressure, which is normally positive or zero; and (3) pore-water pressure, which can be positive or negative but normally negative when the soil is unsaturated and all three phases of the soil are present.

There are several ways to combine these stresses into sums or differences or pairs, but the objective is to find the minimal combinations that control volume change and shear strength of unsaturated soils. These stress variable combinations also need to be measurable and readily used in engineering practice.

Visualizing how these stresses act helps students and engineers understand the behavior of these three stresses. Total normal stress is compressive and therefore tends to push grains together. Positive pore-air pressure tends to push grains apart since field conditions are normally atmospheric. Unsaturated soils have negative pore-water pressure that tends to pull grains together.

3.2.3 Stress State Variables

Because the unsaturated soil is a three-phase medium, the stress state variables are developed from the three individual constituent stresses: total stress, pore-air pressure, and pore-water pressure. Total stress, σ , is always greater than zero and always greater than the pore-air pressure, u_a ; therefore, the difference ($\sigma - u_a$) is called the net normal stress. The net normal stress (which is always positive) corresponds to a net pressure that tends to push the grains together. If the pore-air pressure is greater than the total stress, then the soils will blow up and this is not a condition of interest in traditional geotechnical engineering. Pore-air pressure is considered to be atmospheric above the ground surface when the degree of saturation is low and the air voids are interconnected. Since the pore air pressure is evaluated as a gauge pressure, it is typically zero or very close to zero under these conditions. The pore-water pressure can be positive, zero or negative, but it is always negative when the soil is unsaturated and positive when the soil

is fully saturated. The difference between the pore-air pressure and pore-water pressure ($u_a - u_w$) is the net fluid pressure, which is called soil suction or more specifically, matric suction. Matric suction is almost always positive and relates to the net pressure that tends to pull the soil grains together. The net normal stress and matric suction are the measurable two stress state variables that describe the stress state of the three-phase unsaturated soil material.

The two stress state variables (matric suction and net normal stress) are chosen because they are measurable and consistent with a macro-level continuum mechanics approach which is traditionally used in geotechnical engineering and other civil engineering applications. Research has shown that matric suction and net normal stress control soil deformation and shear strength of unsaturated soils (Fredlund and Morgenstern, 1977). These stress state variables can be expressed in the form of tensors. Figure 3.1 demonstrates the stress tensors for unsaturated soils for the simplified case where total stresses are represented as principal stresses. The two independent stress tensors for an unsaturated soil should be included in the lecture module to help students visualize the stress state variables in the most general tensor form, which represents the state of stress at a point. Students should be reminded that this continuum mechanics approach is the same approach that was used in their introductory mechanics of materials course. Students should be reminded that the stress tensor is the most general representation of the state of stress at a point in a continuous medium.

$$\begin{aligned}
 & \begin{bmatrix} (\sigma_x - u_a) & \tau_{yx} & \tau_{zx} \\ \tau_{xy} & (\sigma_y - u_a) & \tau_{zy} \\ \tau_{xz} & \tau_{yz} & (\sigma_z - u_a) \end{bmatrix} \begin{bmatrix} (u_a - u_w) & 0 & 0 \\ 0 & (u_a - u_w) & 0 \\ 0 & 0 & (u_a - u_w) \end{bmatrix} \\
 & \text{(a)} \qquad \qquad \qquad \text{(b)}
 \end{aligned}$$

Figure 3.1 Stress Tensors (Principal Stress Plane Representation) for an Unsaturated Soil

(a) Net Normal Stress Tensor (b) Matric Suction Tensor

It is necessary to explain the unsaturated soil response when one of the stress state variables changes. For example, when the matric suction is constant, with an increase of net normal stress, the soil becomes stiffer and stronger. When the net normal stress is constant and there is an increase of matric suction (the water pressure becomes more negative), the soil becomes stiffer and stronger. It will be helpful to consider a familiar simple example of a sand castle to understand how matric suction tends to pull soil grains together providing strength and stiffness to a soil. When building a sand castle, it is the matric suction (water in tension) that tends to pull the grains of sand together providing strength and stiffness. When attempting to build a sand castle that is completely dry (no water occupying the void space), a castle cannot be built because the sand particles will simply flow. It should also be explained that this behavior is different when dealing with clays because with clay material is very difficult to completely dry the soil to a point where there is no water in the void spaces – therefore there will always be some soil suction. When some water is added to the sand (but not too much), matric suction develop in the soil mass and this soil suction provides strength and stiffness to the soil. The matric suction is pulling the sand grains together and that is why the sand castle can be built and remains stable. In this case, the matric suction is effective in controlling the

mechanical response of the soil. Also, if the matric suction is just the right magnitude, then a brick or weight can be placed on top of the sand castle because the sand castle can also support some significant net normal stress. This example of the sand castle will help aid in understanding how matric suction of unsaturated soils affects the strength and stiffness of soil.

3.2.4 Processes Leading to Changes Stress State Variables

There are some common field circumstances that change the soil suction of a soil that should be addressed by the instructor during the presentation of the stress state module. The two most common sources of change in soil suction are wetting and drying of the soil. When the soil is wetted, the water content of the soil increases and subsequently the pore-water pressure becomes less negative. When the soil is dried the pore-water pressure becomes more negative, and the soil particles will be pulled together more tightly.

When the soil is wetted, the less tightly pulled together grains will typically result in some increase in the volume of the soil. The increase in volume for granular sands is usually small but for many clay soils, the increase in volume is large which is why some highly plastic clays are referred to as expansive soils. When the effect of wetting causes the soil to immediately increase its density significantly, this soil type is known as collapsible soils. The collapse of soils is most common when the soil is subjected to some significant net normal stress.

As the soil is being dried, the water content decreases and the pore-water pressure becomes more negative. When the pore-pressure becomes more negative, the soil grains are pulled together more tightly and some decrease in volume of the soil may occur.

The soil response to the change in matric suction is important for students to understand. The key point is that changes in soil matric suction (water content) result in changes in volume and changes in shear strength for an unsaturated soil.

There can also be a change in net normal stress that can affect the response of a soil. When there is a change in the net normal stress, it is typically due to the change in the total stress. The most common response of the soil due to an increase in total stress (e.g. a building or surcharge load is added) is compression of the underlying soil and a corresponding settlement of the building. When the total stress is decreased (e.g. removal of a fill), there may be an increase of volume causing the soil layer to expand. The important concept to understand is that with any change in the total stress, the net normal stress will change, and a response of the soil is to be expected.

3.2.5 Transition from Unsaturated to Saturated Soil Conditions

When an unsaturated soil approaches saturation, the void spaces between the soil grains fill with water and the air space becomes discontinuous (not interconnected). Therefore, as an unsaturated soil approaches saturation by wetting, the pore-air pressure approaches the pore-water pressure and the matric suction approaches zero. As a result, for saturated soils, the remaining stresses are the total stress and pore-water pressure (pore air pressure is no longer a player). When the soil is saturated, the stress state is a function of total stress and pore-water pressure. In the saturation condition, the pore-

water pressure is positive (such as the case below the groundwater table) and tends to push the soil grains apart. The pore-water pressure above the groundwater table is negative which tends to pull the soil grains together. Only when a soil is saturated the soil is a two-phase medium rather than a three-phase medium, even though a saturated soil may have small negative pore-water pressure, such as in lower regions of the capillary zone just above the groundwater table. Students need to grasp this transition from unsaturated to saturated soil conditions, and it should be discussed that this transition is smooth. Thus, unsaturated soils represent the general case, with saturated soil conditions being a special case.

For the saturated soil conditions, it is possible to combine the total stress and pore-water pressure into one net stress that is effective in controlling the deformation response and shear strength of saturated soils. This net stress is called the effective stress, σ' , (Terzaghi, 1943) and is defined as:

$$\sigma' = \sigma - u_w \dots\dots\dots (3.1)$$

It is also important to introduce the effective stress tensor as seen in Figure 3.2 to represent the state of stress for a saturated soil at a point. It is necessary to explain what happens to the unsaturated soil stress state tensors once the soil reaches the saturation condition. This can be explained by restating that the pore-air pressure becomes equal to the pore-water pressure and therefore, the matric suction tensor disappears and the pore-water pressure replaces the pore-air pressure in the net normal stress tensor which results in the effective stress tensor for a saturated soil.

$$\begin{bmatrix} (\sigma_x - u_w) & \tau_{yx} & \tau_{zx} \\ \tau_{xy} & (\sigma_y - u_w) & \tau_{zy} \\ \tau_{xz} & \tau_{yz} & (\sigma_z - u_w) \end{bmatrix}$$

Figure 3.2 Effective Stress Tensor for the Saturated Condition

3.2.6 Stress State Module Summary

In summary, the stress state variables lecture module is to be introduced using the macro-level approach using the net stress and matric suction concepts. This will be easier for students to understand since continuum mechanics, macro-level approach is traditionally used in describing engineering materials. This continuum mechanics approach should have been used in introductory mechanics of materials courses that students would have already taken. Using the macro-level approach for the stress state lecture module is best because it is the approach most widely used in engineering applications.

3.3 Soil-Water Characteristic Curve Lecture Module

The soil-water characteristic curve has an important role in the determination of unsaturated soil property functions. The SWCC is used to estimate the matric suction of the soil at a certain water content. This relationship is used in the estimation of unsaturated soil properties and in the deformation and shear strength analyses. The SWCC is extensively used and it is essential for the students to understand its use in engineering applications for unsaturated soils. It will also be helpful for students to get exposed to different methods available in order to construct or estimate the SWCC of a particular soil. These methods, along with the axis translation technique will be presented in the laboratory module.

3.3.1 Surface Tension and Matric Suction

Matric suction is commonly associated with the capillary phenomenon arising from the surface tension of water (Fredlund et al., 2012). The void space in an unsaturated soil can be considered equivalent to a capillary tube as shown in Figure 3.3. The water in the tube rises due to surface tension that occurs at the interface between surfaces of water, glass and air. For a soil, surface tension occurs between the surfaces of water, soil grains and air. Surface tension results from intermolecular forces acting in the air-water interface and causes the surface of the water in the capillary tube to be curved. This interface is called the meniscus. The air-water interface is subjected to a pore-air pressure, u_a , which is greater than the pore-water pressure, u_w . The difference between the pore-air pressure and pore-water pressure is called the matric suction. In traditional undergraduate instruction, the capillary soil model is presented, but the term matric suction and the fact that the matric suction is a stress state variable is not generally not discussed. It is important for the instructor to make the connection between capillary stresses and the matric suction as a stress state variable.

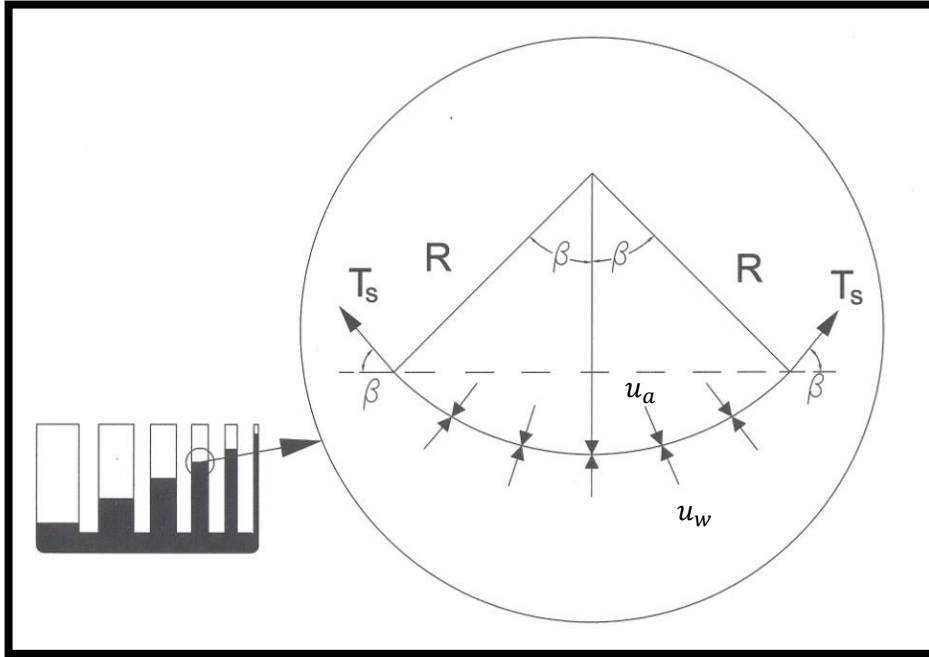


Figure 3.3 Capillary Rise of Water Filled Tubes

The relationship between matric suction and the radius of curvature of the meniscus is illustrated by Kelvin's equation:

$$(u_a - u_w)_d = \frac{2T_s}{R_s} \dots\dots\dots (3.2)$$

Where:

T_s = Surface tension

R_s = Radius of curvature of the meniscus

$(u_a - u_w)$ = Matric suction at the air-entry value

The radius of curvature is inversely proportional to matric suction. The smaller the capillary tube, the smaller the radius of curvature, and the higher the capillary rise as shown in Figure 3.3. By analogy, the smaller the pore size, the smaller the radius of curvature, and higher the matric suction that can be developed. Granular soils such as sands have bigger pores than fined grained materials. Since clays have smaller pore sizes,

they will sustain greater matric suction than granular soils at the same water content. As the soil dries, the water regresses into the pores and the radius of curvature decreases causing the matric suction to increase. The amount of water relative to the amount of air in the soil pore space is therefore related to the radius of curvature. As the water content decreases, the radius of curvature decreases, and the matric suction increases. Hence, the drier the soil, the greater the matric suction. It is important for students to understand the relationship between pore size of a soil, water content, and matric suction. Students should understand that there will be a difference in matric suction values at different water contents, and that the relationship between matric suction and water content will be different for different soil types due to differences pore sizes

3.3.2 Soil-Water Characteristic Curve (SWCC)

The relationship between a measure of water content and the matric suction of a soil is called the soil-water characteristic curve (SWCC). The SWCC is also referred to as water-retention curve, because it represents the amount of water retained by the soil at a particular matric suction stress. A typical SWCC is shown in Figure 3.4. The measure of water content shown in this figure is the volumetric water content, θ_w , which is defined as:

$$\theta_w = \frac{V_w}{V_t} * 100\% \dots\dots\dots (3.3)$$

Where:

V_w = Volume of water

V_t = Total volume of the soil

Other measurements of water content that can be used to create the SWCC are the degree of saturation S , and gravimetric water content, w , as shown by equations (3.4) and (3.5), respectively.

$$S = \frac{V_w}{V_v} * 100\% \dots\dots\dots (3.4)$$

Where:

V_v = Volume of voids

$$w = \frac{M_w}{M_s} * 100\% \dots\dots\dots (3.5)$$

Where:

M_w = Mass of water

M_s = Mass of soil solids

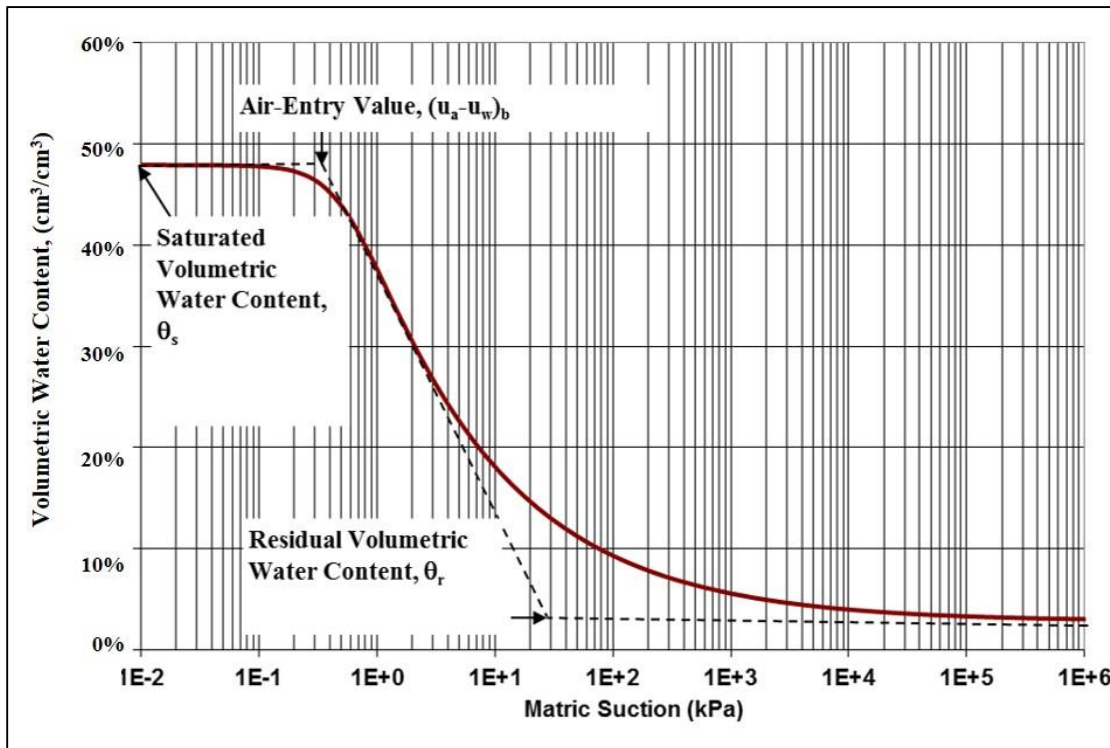


Figure 3.4 Typical SWCC of a Soil

The saturated volumetric water content, air-entry value, and the residual volumetric water content are parameters that can be used to describe the SWCC. The saturated volumetric water content, θ_s , is the water content of the soil at fully saturation condition (zero matric suction). The saturated volumetric water content is the same as the porosity of the soil when the pores are completely filled with water. The air-entry value (AEV) is the matric suction value that must be surpassed before air can enter the void spaces of the soil and will no longer maintain its saturated state. The residual volumetric water content, θ_r , is the volumetric water content from which a change in water content with respect to a change in suction becomes essentially zero. In other words, an increase in matric suction will no longer produce a significant change in volumetric water content. The water content related parameters should be pointed out on the SWCC as shown in figure 3.4 along with a small discussion describing each parameter to the students.

It is important to note that the relationship between matric suction and water content (the SWCC) is non-linear and has a more or less sigmoidal shape. It is helpful to describe the SWCC relationship when either the water content or matric suction increases or decreases, due to its hysteresis nature. When the soil becomes wetted (increase in water content), the pore-water pressure becomes less negative (decrease in matric suction). As the degree of saturation of the soil approaches 100%, the pore-water pressure approaches the pore-air pressure, and the matric suction approaches zero. When the soil is being dried, the pore-water pressure becomes more negative (increase in matric suction). When the soil is very dry, the matric suction becomes quite high, and approaches a value of about 1×10^6 kPa for a completely dry state (Fredlund et al., 2011).

Experimental data have previously shown that the matric suction of a soil reaches a maximum value of approximately 1×10^6 kPa at zero water content (Fredlund & Xing, 1994).

When plotting the SWCC, the matric suction is plotted on a log scale and the water content measure is plotted arithmetically. The matric suction is plotted on a log scale because there is a very wide range of matric suction values associated with moisture conditions of interest in geotechnical engineering. The log scale matric suction is commonly plotted on the horizontal axis while the water content is plotted on the vertical axis.

3.3.3 SWCC for Different Soil Types

The shape of the SWCC is dependent on the type of soil. The amount of fines and the plasticity index of a soil influences the SWCC. Figure 3.5 shows SWCC for different soil types such as sand, silt, and clay. Notice that at the same matric suction value, the plastic soil has a high water content measure than a non-cohesive soil. Clay soil tends to hold more moisture at a certain matric suction than sand. In introducing students to the SWCC, it should be mentioned that the smaller the soil pore sizes (particle size), the more water the soil will retain at a certain matric suction. That is why Figure 3.5 shows that a clay retains more water than a silt and a silt retains more water than a sand at a given value of matric suction.

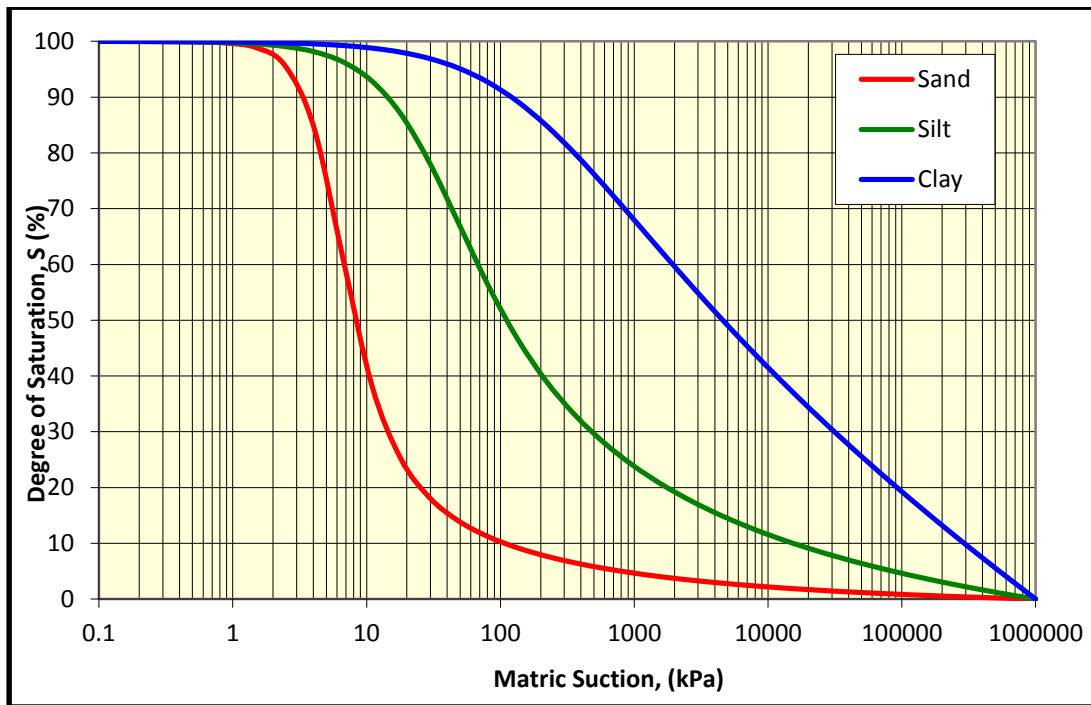


Figure 3.5 SWCC for Sand, Silt and Clay

3.3.4 Development of SWCCs through Mathematical Models

The development of a SWCC for a particular soil can be done through laboratory testing, and requires several points on the SWCC to be measured. With a few measure data points from laboratory testing, several mathematical models are available to construct the entire SWCC for a particular soil. Some of the most commonly used mathematical models developed are the van Genuchten model (1980), the Fredlund and Xing (1994) model, and Pereira and Fredlund (2000) model. The process of fitting experimental suction data to one of the proposed equations requires a minimum number of experimentally obtained suction measurements, depending upon the number of unknown parameters in the chosen function. The more measured data points attained, the better the estimate of the SWCC for a particular soil. One of the most commonly used

equations to construct a SWCC for a particular soil is presented by Fredlund and Xing (1994):

$$\theta_w = C(\psi) * \left[\frac{\theta_s}{\left[\ln \left[\exp(1) + \left(\frac{\psi}{a} \right)^b \right] \right]^c} \right] \dots\dots\dots (3.6)$$

Where:

ψ = Matric suction= $(u_a - u_w)$

θ_s = Saturated volumetric water content

a = Parameter related to the air-entry value of the soil (kPa)

b = Parameter related to the rate of water extraction once the air-entry value has been exceeded

c = Parameter related to the residual water content

The $C(\psi)$ term is a correction factor that forces the curve to 1×10^6 kPa matric suction at zero water content. The correction factor is defined as:

$$C(\psi) = \left[1 - \frac{\ln \left(1 + \frac{\psi}{h_r} \right)}{\ln \left(1 + \frac{10^6}{h_r} \right)} \right] \dots\dots\dots (3.7)$$

Where:

h_r = Fitting parameter related to the suction corresponding to the residual water content

Therefore, when the matric suction, ψ , is equal to 1×10^6 kPa, the water content calculated in equation (3.6) is zero.

3.3.5 SWCC Prediction

When measured matric suction data from laboratory testing is not available, the SWCC can be estimated using grain-size distribution parameters and other soil

parameters. These relationships are based on correlations with commonly obtained soil index parameters such as Atterberg limits and grain size data (for plastic soils) and grain-size distribution (for non-plastic soils). In some cases, SWCCs are estimated using a large database (SoilVision Systems) of SWCC's by matching certain key soil characteristics of the soil. Zapata (1999) proposed equations to predict the fitting parameters for the Fredlund and Xing (1994) equation for plastic soils (Zapata et al., 2000). The following equations were proposed:

$$a = 0.00364(wPI)^{3.35} + 4(wPI) + 11 \dots\dots\dots (3.8)$$

$$\frac{b}{c} = -2.313(wPI)^{0.14} + 5 \dots\dots\dots (3.9)$$

$$c = 0.0514(wPI)^{0.465} + 0.5 \dots\dots\dots (3.10)$$

$$\frac{h_r}{a} = 32.44e^{0.0186(wPI)} \dots\dots\dots (3.11)$$

Where:

wPI = Percent passing the #200 U.S. standard sieve time the Plasticity index divided by 100

Once the parameters are replaced in the Fredlund and Xing (1994) equation, the family of SWCC curves presented in Figure 3.6 can be obtained. Note that the family of curves presented by Zapata (1999) yields for both plastic and non-plastic soils. The family of curves for non-plastic soils is based on the Diameter 60 (D_{60}) of the grain-size distribution. Torres (2011) found that the D_{10} particle size produced improved correlation coefficients than using the D_{60} particle size for non-plastic soils. Figure 3.7 shows the family of SWCCs for non-plastic soils recommended by Torres (2011) combined with the

family of curves for plastic soils recommended by Zapata (1999). As stated before, these curves make use of the Fredlund and Xing (1994) equation.

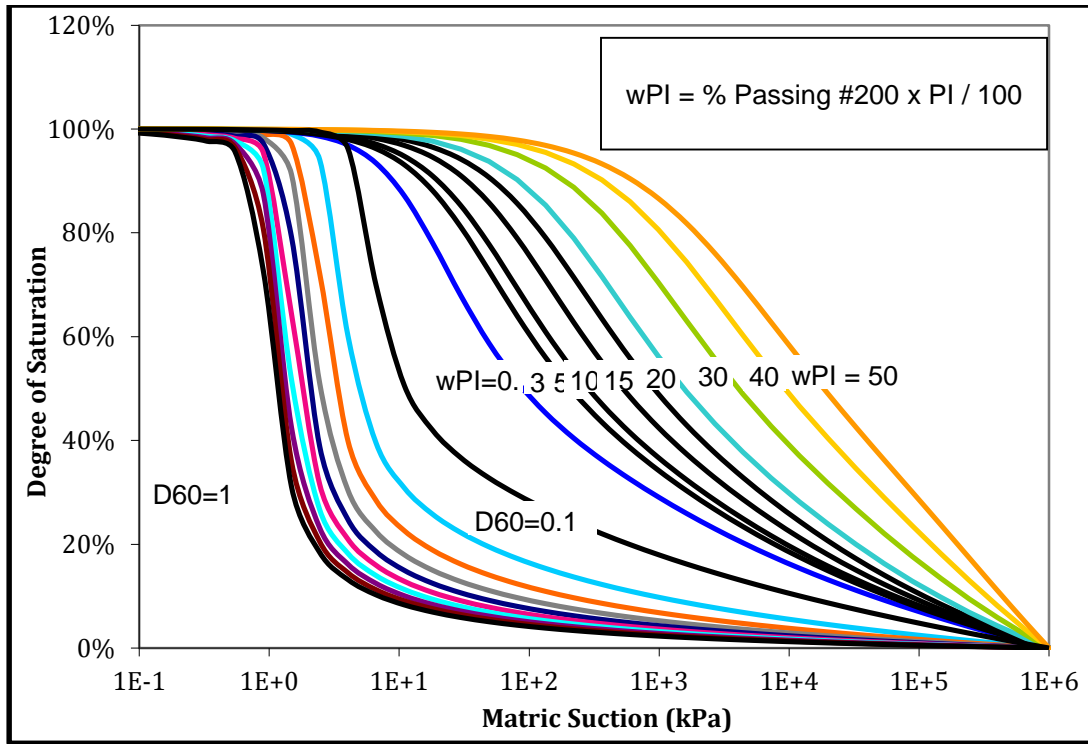


Figure 3.6 Family of SWCCs for Plastic and Non-Plastic Soils (Zapata, 1999)

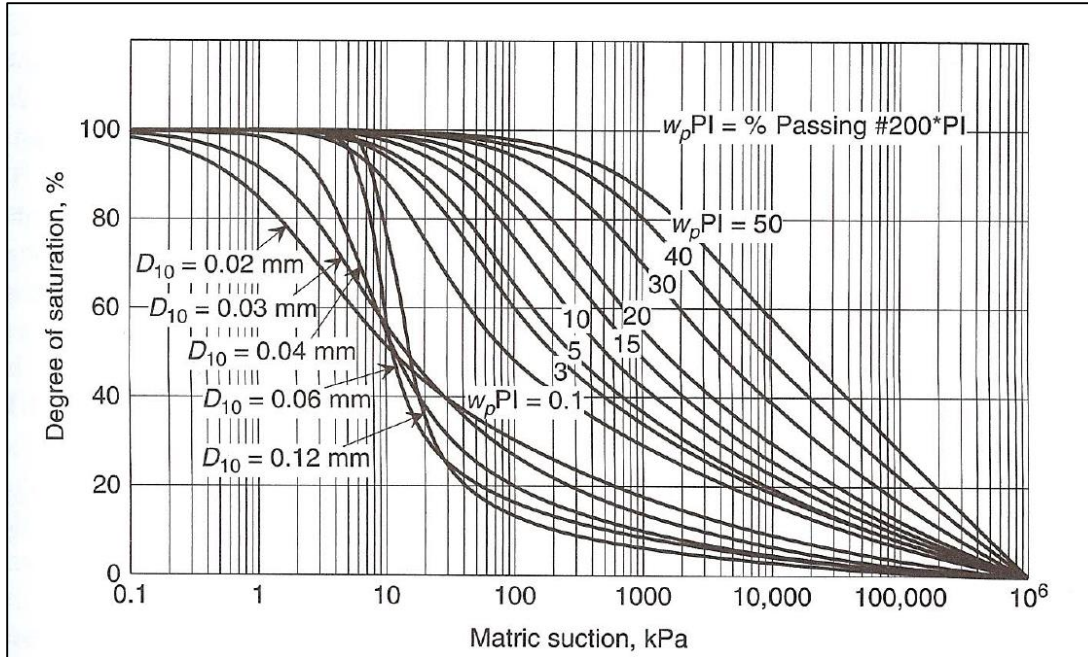


Figure 3.7 Family of Curves using Torres Model for Non-Plastic Soils (Fredlund et al., 2012)

3.3.6 Estimation of Shear Strength for Unsaturated Soils

One use of the SWCC is in the estimation of shear strength for unsaturated soils. There are a few shear strengths equations that incorporate SWCC characteristics in the estimation of unsaturated soil shear strength. Vanapalli et al. (1996b) suggested a shear strength equation that involved a normalization of the SWCC between the saturated condition and the residual volumetric water content condition (Fredlund et al., 2012). Vanapalli et al. (1996b) proposed a general equation for shear strength for unsaturated soils and is defined as:

$$\tau = c' + (\sigma - u_a) \tan \phi' + (u_a - u_w) \left(\frac{\theta_w - \theta_r}{\theta_s - \theta_r} \right) (\tan \phi^b) \dots \dots \dots (3.12)$$

Where:

c' = Cohesion of the soil

$(\sigma - u_a)$ = Net normal stress

$(u_a - u_w)$ = Matric suction

θ_w = Volumetric water content

θ_s = Volumetric water content at 100% saturation

θ_r = Volumetric water content at residual suction

ϕ' = Angle of internal friction associated with the net normal stress state variable

ϕ^b = Angle indicating the rate of increase in shear strength with respect to a change in matric suction

Fredlund et al. (1996) also developed a shear strength equation incorporating the SWCC written in terms of dimensionless water content, Θ^κ . This shear strength equation is nonlinear due to the nonlinearity of the SWCC. Fredlund et al. (1996) shear strength equation is defined as:

$$\tau = c' + (\sigma - u_a)\tan\phi' + (u_a - u_w)[\Theta^\kappa]\tan\phi' \dots\dots\dots (3.13)$$

Where:

Θ^κ = Normalized volumetric water content defined by $\frac{\theta_w}{\theta_s}$, which is also equal to the degree of saturation

κ = Fitting parameter for the SWCC

3.3.7 Estimation of Hydraulic Conductivity of Unsaturated Soils

Another common use of the SWCC is in the estimation of hydraulic conductivity of unsaturated soils. Van Genuchten (1980) proposed a hydraulic conductivity function for unsaturated soils based on the fitting parameters associated with the SWCC and is expressed as:

$$k_w = k_s \frac{[1 - \alpha \psi^{n-1} (1 + \alpha \psi^n)^{-m}]^2}{[1 + (1 + \alpha \psi^n)^{\frac{m}{2}}]} \dots\dots\dots (3.14)$$

Where:

k_w = Hydraulic conductivity of an unsaturated soil

k_s = Saturated hydraulic conductivity

ψ = Matric suction = $(u_a - u_w)$

$m, n, \text{ and } \alpha$ = SWCC fitting parameters

3.3.8 Measuring Matric Suction

It is important to be able to measure soil suction in the laboratory and to be able to estimate or measure soil suction in the field. It is important because soil suction is one of the two stress state variables affecting volume change and shear strength for unsaturated soils. Matric suction can be measured directly or indirectly. Direct methods are used to measure the negative pore-water pressure of the soil. The pore-air pressure in the field is generally atmospheric and therefore, the matric suction is equal to the negative pore-water pressure.

$$\psi = (u_a - u_w) = 0 - u_w = -u_w \dots\dots\dots (3.15)$$

Some equipment for direct measuring matric suction are Tempe cells, pressure cells, and tensiometers all of which use the axis translation method. Tensiometers are a direct method to measure low suction values up to 100 kPa. Tempe cells and pressure cells both measures the negative pore-water pressure up to 1500 kPa. The axis translation technique is the most common method for the direct measurement of soil matric suction. The axis translation technique is covered in the pre-lab lecture module and demonstrated in the laboratory module.

3.4 Axis Translation Pre-lab Lecture Module

The axis translation lecture module is intended to be a brief module in comparison with the previous two lecture modules since it is only intended as a small lecture before the laboratory testing. Instruction on axis translation methods for control and measurement of matric suction is critical in this lecture module. This module will help students understand how the axis translation technique works and how it is incorporated in the laboratory testing to obtain the SWCC.

3.4.1 Matric Suction

Some of the SWCC lecture module material will be included in the axis translation module to serve as a refresher on the concepts learned. The purpose of the axis translation technique is to determine the matric suction of the soil at different water contents. Matric suction is related to the capillary phenomenon, which is the rise of water in a tube due to the surface tension of the water. Pores in a soil mass are similar to small radius capillary tubes in which the soil-water is raised above the ground water table. The smaller the particle size, the higher the capillary rise will occur above the water table. The water has negative pressure with respect to air pressure, which is normally atmospheric. Since the water has a negative pressure, the water is in tension under unsaturated conditions. When the degree of saturation of a soil is very low, the pore-water pressure can be highly negative.

The water level in the capillary tube is curved and is called the meniscus. The radius of the meniscus is inversely proportional to the matric suction. The relationship is

shown in Kelvins equation (3.2). The lower the radius of curvature, the higher the matric suction.

3.4.2 Axis Translation in the Lab

How do we obtain matric suction? One way to measure matric suction is to directly measure or control the negative pore-water pressure and pore-air pressure effectively translating the reference pore-air pressure from atmospheric conditions to a higher air pressure as required to prevent cavitation in the measurement device. Since the pore-water pressure is usually highly negative in an unsaturated soil, measuring or controlling the pore-water pressure in the laboratory often requires increasing the pore-air pressure to avoid cavitation of water in the measurement device. To avoid cavitation, high air-entry ceramic disks are used to separate the air and water. If the disk is saturated with water, air cannot enter and pass through the disk if the pressure does not exceed the air-entry value of the disk, since the air-water interface resists the flow of free air. The difference between the air pressure above the interface and the water pressure below is the matric suction. The maximum matric suction that can be maintained across the surface of the high air-entry ceramic disk is called the air-entry value.

A high air-entry disk can only separate the air and water pressure if the soil's matric suction is not greater than the disk's air-entry value. Once the matric suction exceeds the air-entry value of the disk, air will pass freely through the disk and enter the measuring system. If this occurs, it will cause an inaccurate measurement of the soil's pore-water pressure. Students need to know the importance of high air-entry ceramic disks and the reason for their use during testing.

To directly measure matric suction in the lab, the axis translation technique is used. The procedure of axis translation should be briefly explained prior to conducting the laboratory. A detailed manual was developed for conducting the SWCC laboratory module. The approach that will be followed can be briefly described as follows: Place a soil specimen on top of saturated high air-entry disk in an air pressure chamber. It is important to make sure the air-entry of the disk is higher than the matric suction you wish to measure. Then place a token load on the sample to ensure the soil and the disk are in contact. The placement of the specimen onto the ceramic disk and the assemblage of the cell chamber are performed as rapidly as possible (Fredlund et al., 2012). Keep the water pressure in the compartment chamber below the air-entry disk as close to zero as possible by increasing the air pressure in the chamber to prevent water movement into or out of the specimen.

A pressure cell apparatus is used to measure the negative pore-water pressures. Use the air pressure and water pressure at equilibrium to determine the matric suction. This procedure changes the atmospheric pressure in the chamber to move the origin of reference for the pore-water pressure from the standard level to the final pressure in the chamber and is the reason it is called the axis translation. Cavitation is prevented because water pressure in the measuring system does not become highly negative. The water pressure is usually maintained at zero and a positive air pressure is applied in the chamber. Therefore, different matric suction values can be determined by applying different air pressures to the specimen.

An example of how to measure negative pore-water pressures using a pressure cell apparatus will be very helpful for the students to understand how to use it in the

laboratory. Suppose that a soil specimen has an initial matric suction of 250 kPa when placed on a saturated high air-entry disk. The specimen will immediately tend to draw water up through the ceramic disk. The increase of the chamber's air pressure tends to mitigate upward water flow through the high air-entry disk. The water content is measured once the system reaches equilibrium (once the upward movement of water stops). By noting the amount of water that have come into or out of the specimen, an adjustment to the initial water content of the specimen is made to obtain the water content consistent with the matric suction of interest. The matric suction can be changed to another value of interest by increasing or decreasing the air pressure while holding the pore-water pressure to zero. Then, the measured matric suction and water content are plotted to develop the SWCC.

3.4.3 Axis Translation Summary

In summary, the air pressure in the pressure cell apparatus is equal to the matric suction when using the axis translation technique when the pore water pressure is held at zero. High air-entry disks are used inside the pressure cell apparatus to separate air and water to prevent air to pass freely through the measuring system that would cause inaccurate measurements. Apparatus such as the Tempe Pressure Cell (Soilmoisture Equipment Corp.) and the oedometer pressure plate device (ex., the SWC-150 device by GCTS) are used in the laboratory to measure water contents at different matric suction values. The advantage of the SWC-150 equipment is that soil volume change measurements can be made, which is helpful in reinforcing the concept that matric suction is a stress state variable that affects soil deformation. Also, net normal stress can

be controlled with the Fredlund SWC-150 device. Although the oedometer type pressure plate device is best for use by geotechnical engineers, the cost of this device could be prohibitive for some institutions. In this case, Tempe cells can be used to perform the laboratory procedure.

3.5 Development of PowerPoint Presentation for the Lecture Modules

A PowerPoint presentation was created for each of the three lecture modules. The purpose of the PowerPoint presentation is for the instructors to use it to present the learning material to the students. This way, it will minimize work for the instructors in putting a lecture plan for the unsaturated soil material. The learning material for each lecture module was summarized and implemented in the slides.

The background format for each slide was important to get right. At first a colored background on each slide was being used for each PowerPoint. Soon after, the research team noticed it would cause an issue for the students. Students will be more hesitant and reluctant to print out the PowerPoint slides for study purposes due to the fact that it will consume a great deal of ink. To mitigate this problem, a new background format was developed that would consider using less ink during printing. Also, certain words or phrases were highlighted in red to emphasize the importance of its meaning. Figures and equations are also used with its associated concepts. Examples were implemented to enhance students understanding of certain concepts that may be initially confusing. The final product of the PowerPoint presentation slides can be seen in Appendix A (Stress State Variables Module), B (Soil-Water Characteristic Module), and C (Axis-Translation Module).

Chapter 4

4 DEVELOPMENT OF LABORATORY MODULE

4.1 Introduction

One of the purposes of this thesis was to create a laboratory manual and recommend a soil type to perform the test that facilitate the introduction of the laboratory module for unsaturated soils into the introductory undergraduate geotechnical course. The main objective for the module is to teach the students how to construct a SWCC using their own data obtained through the laboratory testing. Students will measure the matric suction at different soil moisture contents using the axis translation technique and testing equipment for unsaturated soils. This module assists the students in performing the laboratory test and constructing the SWCC for the soil of interest. Another objective of this chapter is to provide the instructor with the properties of a soil suitable to perform the SWCC laboratory test that allows completing the procedure in a timely manner.

4.2 Development of Laboratory Manuals and Analysis Guide

Certain testing equipment was chosen for the use in the laboratory module. The recommended testing apparatuses for unsaturated soils are the Tempe cells and the one-dimensional oedometer pressure plate device. These devices were chosen due to several advantages. The advantage of the oedometer pressure plate device is that it allows for application of net normal stress and/or measurement of volume change of the specimen in response to changes in matric suction. Since the oedometer pressure plate device is considerably more expensive than the Tempe cell, the Tempe cell has been included as an option for the laboratory module. A laboratory manual was created for each device giving the instructor of the module the option of using either one. Along with the laboratory

manual, a guide for data analysis and construction of the SWCC was created for the students to follow. The data analysis can be difficult to perform if one is not experienced, and therefore, this guide will help the student through the process.

4.2.1 Testing Equipment Proposed for the Laboratory Module

The Tempe pressure cell (shown in figures 4.1 and 4.2) is used to determine the matric suction for a soil sample at a given water content. The Tempe pressure cell has not been designed to withstand higher pressure and can be used to apply a pressure ranging from 0 to 1 bar (100kPa) to the soil sample. This is a relative small, simple device that is more affordable than the oedometer pressure plate. However, the Tempe cell does not allow for control of net normal stress or measurement of volume change. A Tempe cell device, however, could be purchased for approximately \$500 at the time this thesis was written, which is less than 5% the price of the oedometer pressure plate. In spite of the limitations of the Tempe Pressure Cell it is a good device for demonstrating the axis translation concept and for teaching students how to obtain the SWCC.



Figure 4.1 Tempe Pressure Cell (Soilmoisture Equipment Corp.)

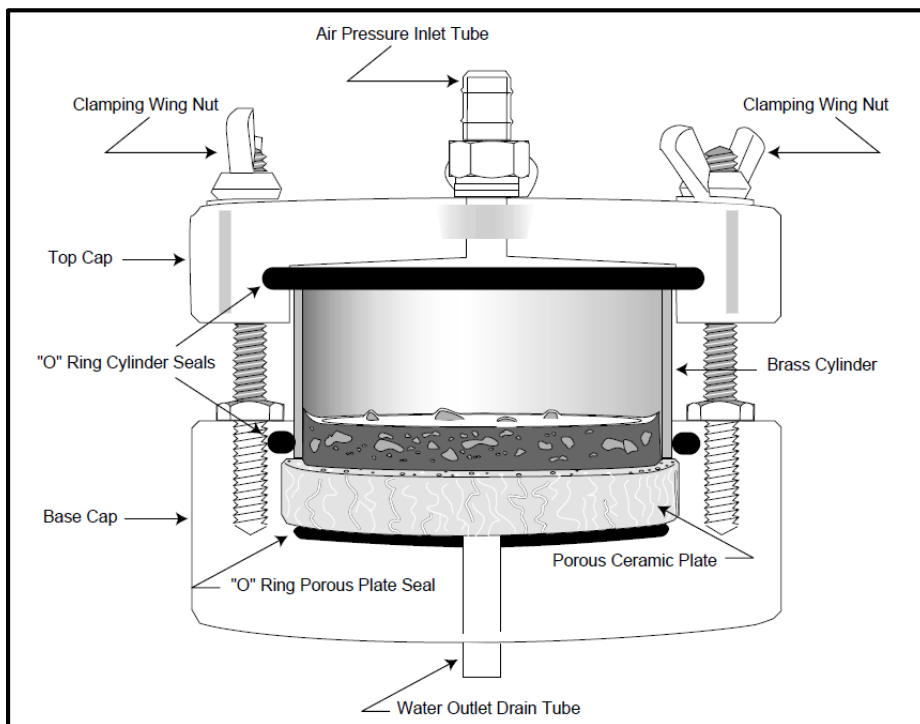


Figure 4.2 Schematic of Tempe Pressure Cell (Soilmoisture Equipment Corp.)

The Fredlund SWC-150 device is a one-dimensional oedometer pressure plate cell as shown in Figure 4.3 and 4.4. It is a relatively simple unsaturated soil testing apparatus that is capable of applying matric suctions while applying a net normal stress. The Fredlund SWC-150 device can apply matric suction values ranging from 0 to 15 bars kPa (1500 kPa) and is capable of applying one-dimensional vertical loading to the soil specimen. This device also allows for measurement of volume change of the soil specimen during the loading process. The Fredlund SWC-150 device could cost about \$12,000 to purchase at the time this thesis was written, but it has several capabilities that a Tempe pressure cell does not have. Currently, this can be considered the best device for demonstrating the role of matric suction and net normal stresses and their effect on soil volume change.



Figure 4.3 Fredlund SWC-150 (GCTS Testing Systems, Tempe, AZ)

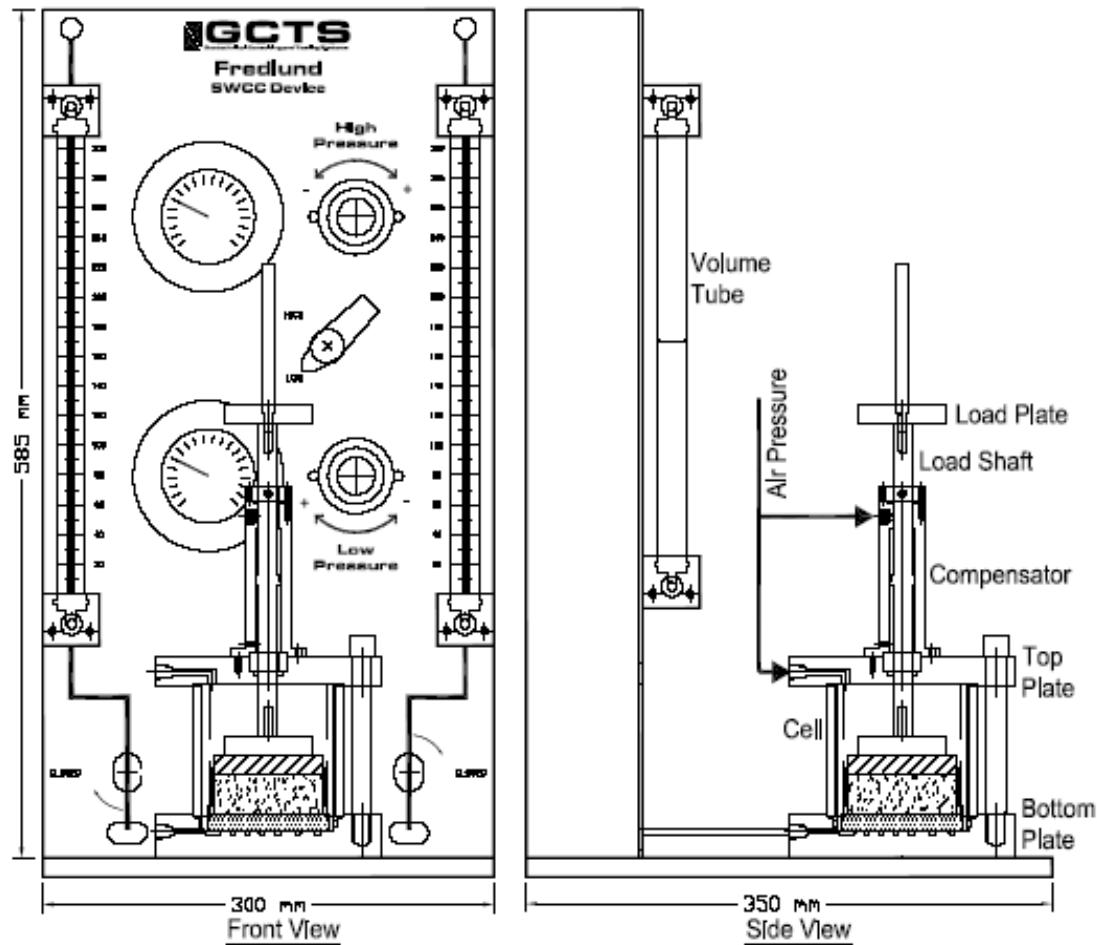


Figure 4.4 Schematic of Fredlund SWCC Device (GCTS Testing Systems, Tempe, AZ)

4.2.2 Laboratory Manual

Two different instruction manuals were developed for students to construct the SWCC during the laboratory module. One manual is for the use of the Tempe pressure cell and the other one is for the use of the Fredlund SWC-150 device. That way, the instructor can choose of the two available equipment options for the laboratory module. The laboratory manuals developed for each device, were built on manuals provided by the equipment manufacturers.

The following sections are included in the laboratory manuals:

1. Introduction: A brief background on SWCC and the purpose of the laboratory module.
2. Apparatus and Supplies: A detailed list of supplies needed for the equipment and module.
3. Samples: This section explains how soil samples used for the module should be handled.
4. Soil Type Recommendation: This section recommends a soil type with a range of soil properties for reasonable equilibrium times and ease of use.
5. Soil Index Property Determinations: This section includes the list of recommended ASTM standard procedures for the determination of each soil property needed to complete the test.
6. Procedure: This section represents a step by step process to conduct the SWCC laboratory test. This includes the preparation for the module, soil sample preparation, and the use of the device.
7. Data: Data sheets to follow throughout the testing procedure are included in this section. This will help students to keep track of the necessary data needed for the analysis section of the laboratory module.

The manufacturer manual of each Tempe pressure cell and Fredlund SWC-150 devices were used extensively in the development of the laboratory manuals. Each manufacturer provided a procedure and helpful hints for using their devices. Modifications were made to aid the students in following each step of the laboratory module with ease. Effort was put in making sure each manual was very detailed so that the students can follow the testing procedure correctly to obtain the best possible results.

A copy of the laboratory manual for the Tempe pressure cell and the Fredlund SWC-150 devices can be seen in Appendix A and B, respectively.

4.2.3 Analysis Guide

The students will be required to construct a soil-water characteristic curve using either the Tempe pressure cell or the Fredlund SWC-150 device. The instructor will be given the option to determine which analysis approach he/she will want their students to use in constructing the SWCC of the soil of interest. Fitting the data obtained to the equation proposed by Fredlund and Xing (1994) and the “one-point method” (Pereira et al., 2006) are the two analysis approaches developed for constructing the SWCC. It would be ideal for the students to try both analyses and compare results, but using just one approach will be satisfactory. However, it should be emphasized that the more points are measured, the better curve can be obtained.

The Fitting process to follow when using the Fredlund and Xing (1994) equation is the more complex of the two approaches. Students will be required to use computer software to fit a nonlinear function based on the squared errors approach. A program similar to Solver in Microsoft Excel® is needed to determine the best-fit parameters for the Fredlund and Xing (1994) equation from the laboratory data obtained. A step-by-step analysis procedure was developed and can be seen in Appendix F. The analysis guide also contains an example of how to construct a SWCC using the Fredlund and Xing (1994) equation in Microsoft Excel®.

The One-point method using the family of SWCC curves is a simple approach that students should follow easily. The guide developed to use the one-point method is

shown in Appendix G. This approach allows for the estimation of the SWCC using correlations between the Fredlund and Xing equation parameters and simple index properties such as the percent passing the #200 sieve (from the grain-size distribution) and the plasticity index (PI) of the soil. Students will be required to determine or be given these soil properties to be able to use the One-point method. The family of curves from Zapata (2000) will be used for the One-point method approach analysis. In this method, students need to obtain only one SWCC data point in the laboratory and use that data point to shift a curve that was obtained based on the aforementioned index properties.

It would be very educational if students use both analysis methods and compare the resulting SWCCs. Students could discuss about the difference between the two SWCCs and the reasons behind it. This exercise should make the students think about the different factors that affect the construction of SWCCs.

4.3 Soil Type Recommendation

It is essential to recommend a certain soil type to use during the laboratory module to minimize frustration on the part of instructor, teaching assistant, and/or students. There are two main goals in the selection of the soil type process: (1) to ensure proper equilibration times, and (2) to make sure the slope of the SWCC is neither too steep nor flat in order to cover a significant portion of the SWCC within the range of suctions that can be controlled with the chosen laboratory equipment.

Certain soil types can take several days to reach equilibrium during testing which is unacceptable because instructors of the laboratory module do not want students to spend that much time on these tests. For example, Dr. Lawrence, from Arizona State University, stated that he wanted his students to be able to finish their tests within two days

from the start of the laboratory module. Anything outside of this time frame was unacceptable and might jeopardize his plan of conducting the laboratory module. Many professors (instructors) might feel the same way, and that is why the recommended soil type should ensure short equilibrium times ranging from one to two days maximum.

While the soil type should warrant limited equilibrium times, the SWCC measured data points should span over a range of matric suction at values. The SWCC transition slope should range between suction values of 40 to 1400 kPa so that both the Tempe pressure cell and Fredlund SWC-150 devices could be used for the recommended soil. Also the air entry value of the soil should be less than 100 kPa, the upper limit of the Tempe cells. Determining SWCCs for different soil types will assist in determining which soil type to recommend using for the laboratory module.

4.3.1 Testing Equipment Used in the Research

Two different types of testing equipment were used for the soil type determination. These devices were the same devices proposed in the laboratory module: the Tempe pressure cell and the Fredlund SWC-150 devices. The Tempe pressure cell was used for low suction values ranging from 0 to 100 kPa while the Fredlund SWC-150 cell was used for higher suction values ranging from 100 to 1500 kPa.

4.3.2 Soils Used in the Research

Three different types of soil were used in the research: sand, silt, and clay. Each soil type represented different equilibrium times, air entry values, and SWCC curves. Basic index soil properties and gradation were determined for each soil used in this research.

A poorly graded sand (SP) was the first soil used in the research. The minimum and maximum dry unit weight tests were conducted on the soil. The minimum dry unit weight of the sand test was performed in accordance to the ASTM D4254 standard. Based on the standard procedure, the oven-dried soil was placed into a container of known volume and the mass of the soil was measured. Knowing the volume of the container and the mass of soil in the container, the minimum unit weight was then calculated. The ASTM D4253 standard was used to determine the maximum dry unit weight of the sand soil. The maximum dry unit weight was determined by placing the oven-dried soil into a mold, applying a 2-lb/in.² dead weight to the top of the soil, and then vibrating the mold to allow the soil to be densified. The maximum dry unit weight was calculated by measuring the mass of the soil and volume of sand-filled mold. Table 4.1 shows the results of the test. The poorly graded sand had a minimum dry unit weight of 14.75 kN/m³ and a maximum dry unit weight of 16.75 kN/m³. The maximum dry unit weight was needed for the preparation of the soil sample for the SWCC test.

Table 4.1 Minimum and Maximum Unit Weight of the Poorly Graded Sand

Minimum Density (kN/m ³)	Maximum Density (kN/m ³)
14.75	16.75

A silt soil from a past Price Club construction site in Scottsdale (Arizona) was also used in the research. This soil is known as the PC silt. The Proctor compaction test was performed on the PC silt to determine its optimum moisture content and maximum dry unit weight. The Proctor compaction was performed in accordance to the ASTM

D698 standard. From the proctor compaction curve shown in Figure 4.5, the optimum moisture content and maximum dry unit weight for the PC silt are 12.1% and 19.45 kN/m³, respectively. The results are summarized in Table 4.2. The optimum moisture content and maximum dry unit weight was needed for compacting the PC soil sample in a consistent manner for testing.

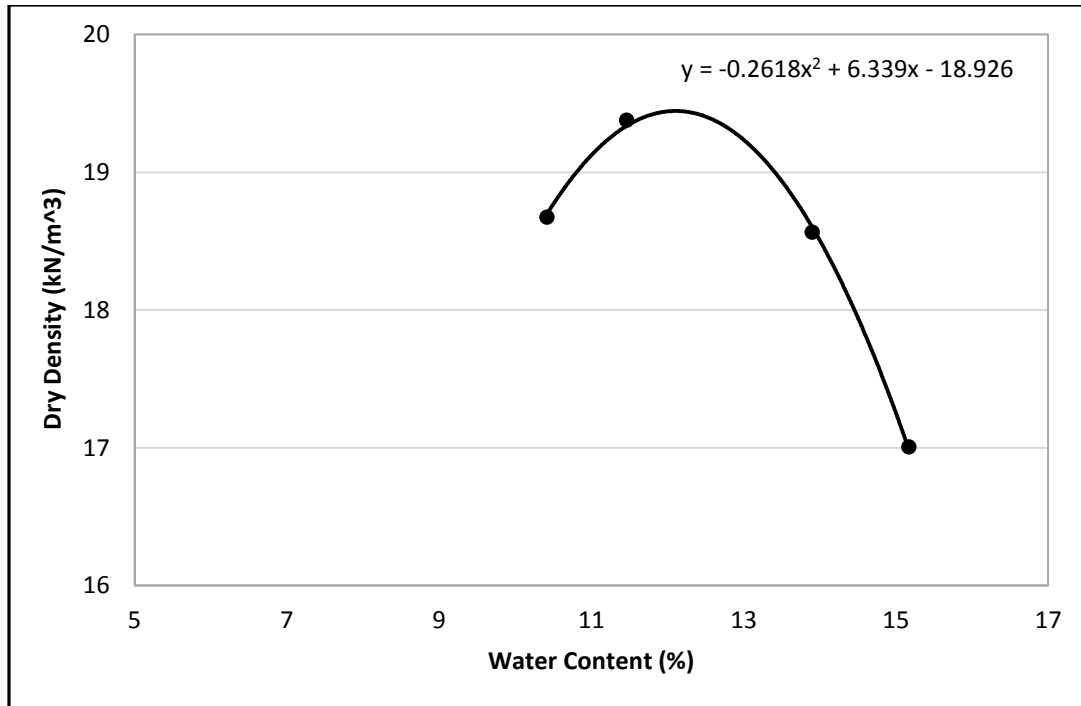


Figure 4.5 Proctor Compaction Curve of PC Silt Soil

Table 4.2 Results from Proctor Compaction on PC Silt

Optimum Moisture Content (%)	Max Dry Density (kN/m ³)
12.1	19.45

Atterberg limits tests were performed on the PC silt to determine its liquid limit, plastic limit, and plasticity index. These soil properties was also needed if the PC silt

would be the soil type recommended for the laboratory module. Table 4.3 shows the results from the Atterberg limits test performed in accordance to ASTM D4318 standard.

Table 4.3 Results from the Atterberg Limits Test

Liquid Limit (%)	Plastic Limit (%)	Plasticity Index (%)
24	18	5

A clay soil from Texas was also used in the research. This soil is referred to as the Texas clay. Proctor compaction was performed on the Texas clay. The compaction test was performed in accordance to the ASTM D698 standard. Figure 4.6 shows the compaction curve. From the compaction curve, the optimum moisture and maximum dry unit weight of the Texas clay were determined to be 28% and 14.75 kN/m³, respectively. The optimum moisture content and maximum dry unit weight was needed to compact the soil sample for testing.

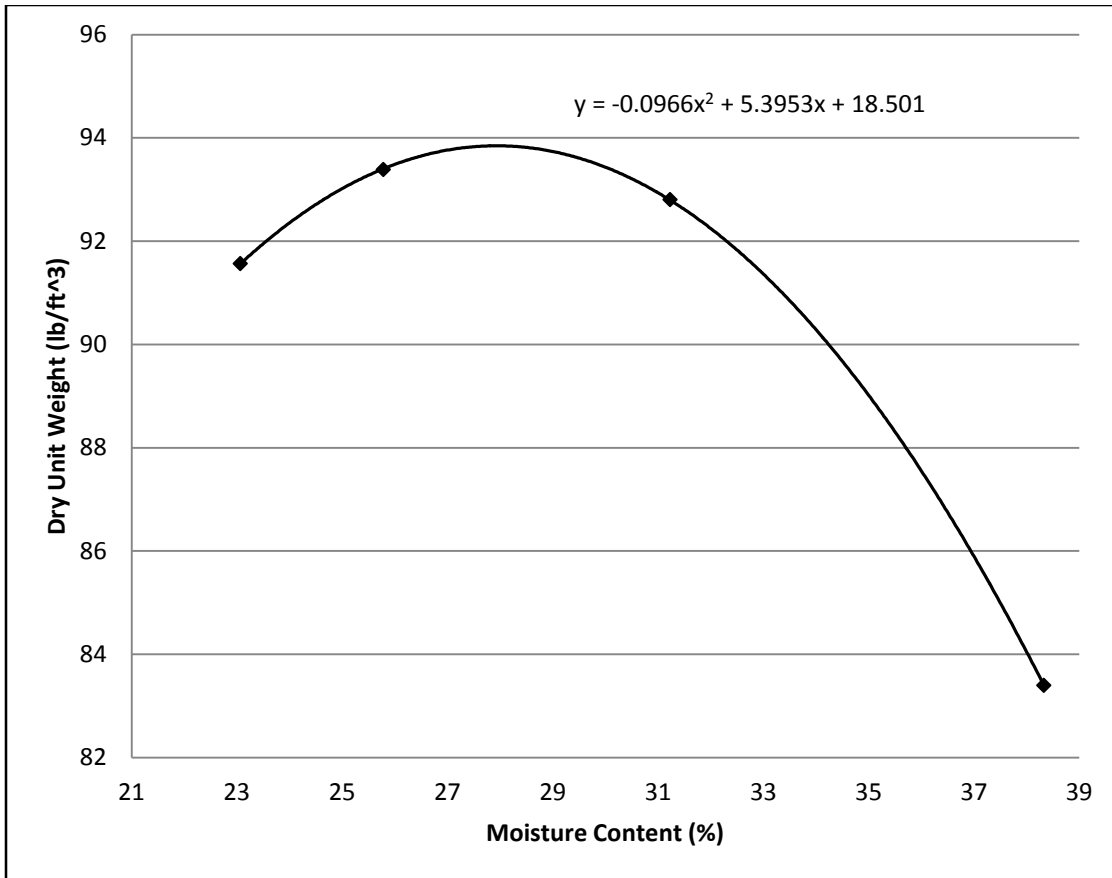


Figure 4.6 Proctor Compaction Curve of the Texas Clay

Table 4.4 Proctor Compaction Results

Optimum Moisture Content (%)	Max Dry Density (kN/m³)
28	14.75

Atterberg limits tests were also performed on the Texas clay. These properties were also needed if the Texas clay would have been chosen to be the soil type recommended for the laboratory module. Atterberg limits tests were performed in accordance to the ASTM D4318. Table 4.5 shows the results obtained from the Atterberg limits tests on the Texas clay.

Table 4.5 Atterberg Limits test Results on the Texas Clay

Liquid Limit (%)	Plastic Limit (%)	Plasticity Index (%)
57	30	27

4.3.3. Soil-Water Characteristic Curve Test Results

Testing on all three soils (poorly graded sand, PC silt, and Texas clay) was performed as described above. The laboratory manuals developed for the laboratory module were used and followed during the SWCC testing on the three soils. Both the Tempe pressure cell and Fredlund SWCC devices were used in the testing process. During the soil specimen preparation, each soil was compacted at 95% maximum dry density and at its optimum moisture content. Once the soil specimen was fully compacted, each soil sample was saturated for a minimum of 24 hours. The high air-entry value disks used for the testing equipment were also saturated with water for a minimum of 24 hours to insure fully saturation of the disks. Once the soil specimen and AEV disks were fully saturated, they were ready to be placed into the testing cells. Water content measurements were determined at different values of matric suction for each soil type. Once the laboratory testing was finished, the analyses for constructing the SWCC for each soil type was performed using Microsoft Excel[®] computer program (Excel 2013).

The Tempe pressure cell was used for the poorly graded sand. From past research experiences, sands tend to have low water content measurements at low suction values. For this reason, the Tempe Pressure Cell was used for all soil specimens for the low

suction range. Table 4.6 indicates the test data obtained from the tests. The test data shows the water content of the soil sample at each tested value of matric suction.

Table 4.6 Poorly Graded Sand Test Data

Matric Suction (kPa)	Water Content (%)
5	10.04
10	9.07
15	8.8
20	8.42
20	8.4
30	7.21
30	6.33
40	5.38
40	5.3
50	5.28
60	4.8
60	4.34
70	4.75
80	4.69
80	4.65
80	4.62

The Fredlund and Xing (1994) equation for SWCCs was used to construct the SWCC of the poorly graded sand soil specimens from the laboratory data. The fitting parameters in the Fredlund and Xing (1994) equation were estimated by using a nonlinear regression analysis. The results are shown in Table 4.7. Once the Fredlund and Xing parameters were determined, the Fredlund and Xing equation was used to construct the SWCC of the sand soil. Figure 4.7 shows the SWCC of the soil along with the data points obtained from the laboratory test. The SWCC of the poorly graded sand shows very low water content measurements at low matric suction values. This means that the sand soil

can only sustain very low suction and does not retain water very well. Given the low measured suction values, the Fredlund SWCC device would not be necessary to use on this type of soil, unless a net normal stress was needed to be included in the analysis or volume change measurements are desired.

Table 4.7 Fredlund and Xing Parameters for the Poorly Graded Sand

Fredlund & Xing Parameters	
a	0.75
n	3
m	0.5
hr	2.5

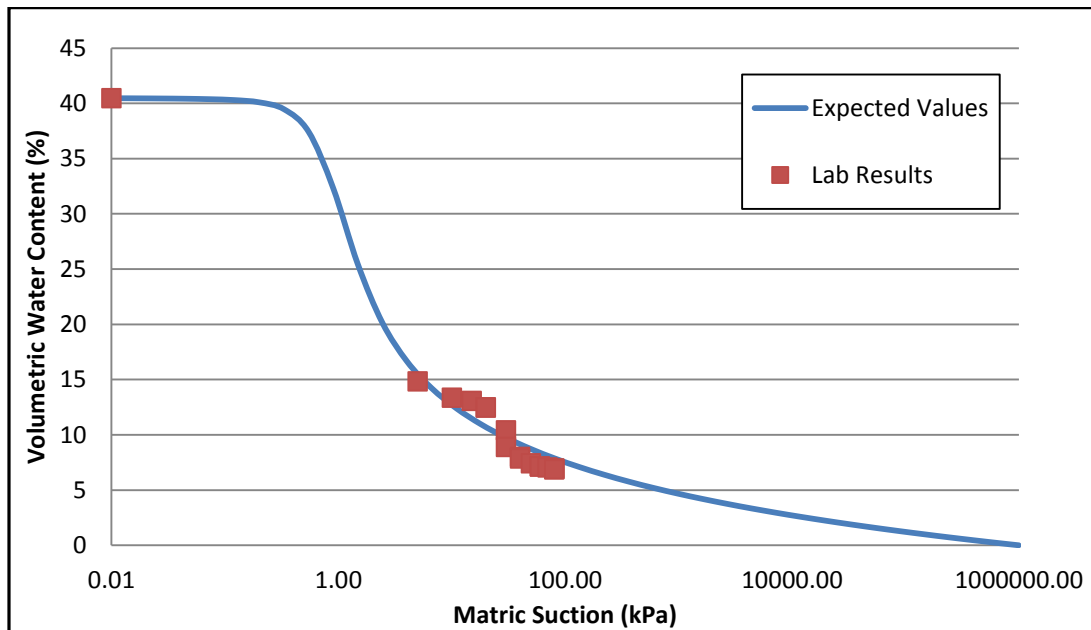


Figure 4.7 SWCC for the Poorly Graded Sand Soil

The Tempe pressure cell and oedometer pressure plate SWCC devices were used for the PC silt. From past research experiences, silts tend to span a wide range of matric

suction values at different water content measurements. For this reason, both Tempe pressure cell and Fredlund SWCC devices were used for all soil specimens for the PC silt soil. Table 4.8 indicates the test data obtained from the tests. The test data shows the water content of the soil sample at each matric suction value.

Table 4.8 PC Silt Test Data

Matric Suction (kPa)	Water Content (%)
5	29.9
10	25.88
15	25.05
20	24.73
20	23.78
30	22.96
30	23.2
40	16.37
40	17.63
50	14.95
60	14.53
60	15.01
70	14.52
80	15.05
80	15.15
80	15.01

The Fredlund and Xing (1994) equation for SWCCs was used to construct the SWCC of the PC silt specimens from the laboratory data. The fitting parameters in the Fredlund and Xing (1994) equation were estimated by using a nonlinear regression analysis. The results are shown in Table 4.9. Once the Fredlund and Xing parameters were determined, the Fredlund and Xing equation was used to construct the SWCC of the PC silt soil. Figure 4.8 shows the SWCC of the soil along with the data points obtained

from the laboratory test. The results demonstrates a good range of matric suction at different water contents. A silt soil retains more moisture at a given suction value than a sandy soil, but it will not retain as much water as a clayey soil.

Table 4.9 Fredlund and Xing Parameters for the PC Silt

Fredlund & Xing Parameters	
a	44
n	0.8
m	2
hr	5

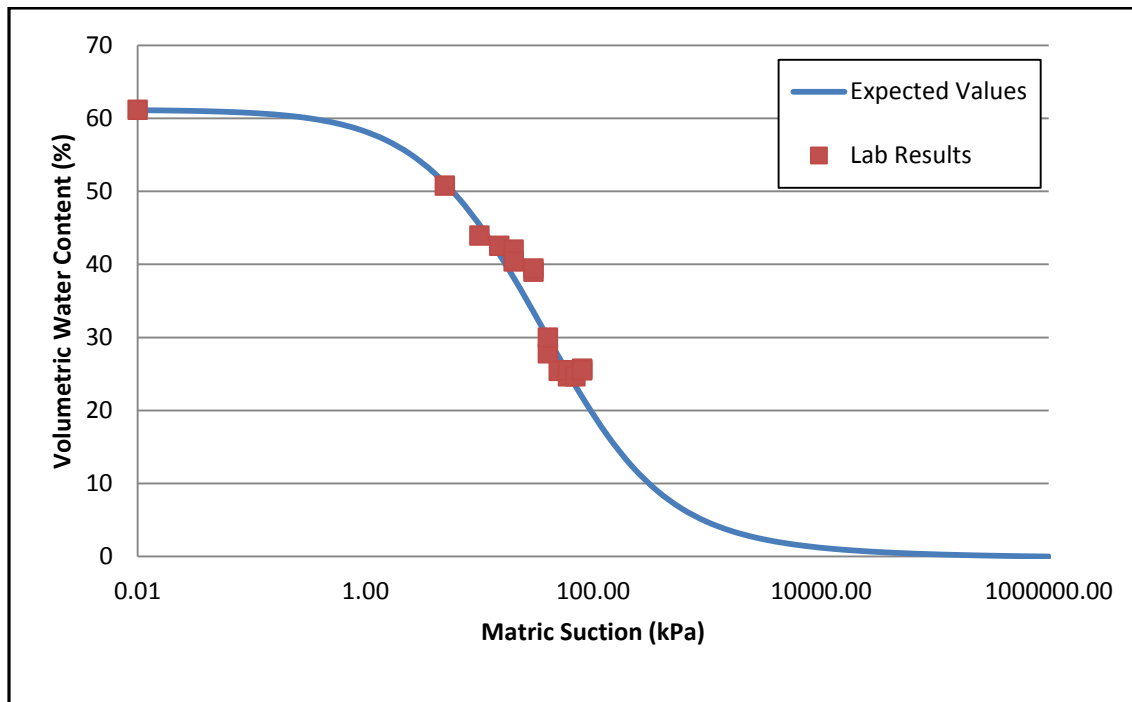


Figure 4.8 SWCC for the PC Silt

The oedometer pressure plate SWCC devices (Fredlund SWCC cells) were used for the Texas clay. From past research experiences, clay soils tend to span a high range of matric suction values at different water content measurements. For this reason, the

Fredlund SWCC device was used for all soil specimens for the Texas clay. Table 4.10 presents the water content and matric suction data obtained from the tests.

Table 4.10 Texas Clay Test Data

Matric Suction (kPa)	Water Content (%)
50	33.9
200	33.5
400	31.1
480	23.2
1450	22.7

The Fredlund and Xing (1994) equation for SWCCs was used to construct the SWCC of the Texas clay specimens from the laboratory data. The fitting parameters in the Fredlund and Xing (1994) equation were estimated by using a nonlinear regression analysis. The results are shown in Table 4.11. Once the Fredlund and Xing parameters were determined, the Fredlund and Xing equation was used to construct the SWCC of the Texas clay soil. Figure 4.9 shows the SWCC of the soil along with the data points obtained from the laboratory test. The SWCC for the Texas clay demonstrates that clay soils retain a lot more water at a given soil suction than the sandy and silty soils, and that clay soils can sustain very high levels of soil suction due to their small pore size. Therefore, it is not possible to use a Tempe pressure cell to obtain the SWCC of the Texas clay because the Tempe cell cannot be used to control suctions higher than 100 kPa. The Fredlund SWCC device is more appropriate for the Texas clay, or any clayey soil for that matter, because soil suctions up to 1500 kPa can be applied.

Table 4.11 Fredlund and Xing Parameters of the Texas Clay

Fredlund & Xing Parameters	
a	80
n	0.7
m	0.8
hr	900

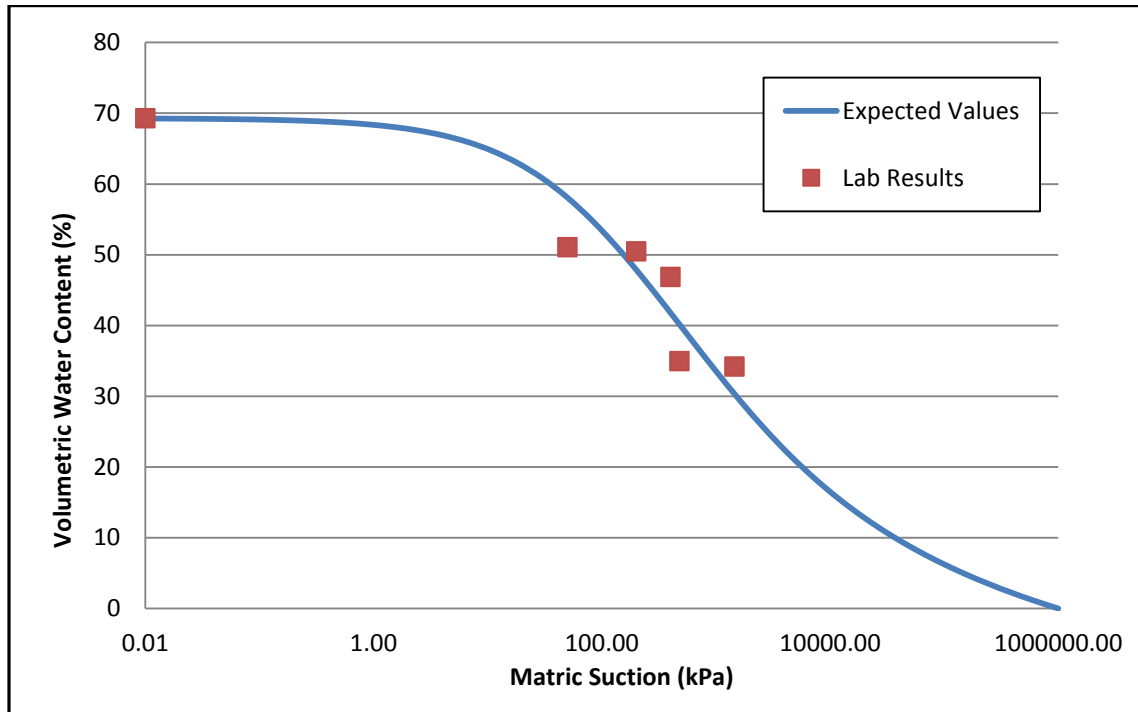


Figure 4.9 SWCC for the Texas Clay

Each soil type experiences different equilibrium times during the testing. The poorly graded sand experienced the shortest equilibrium time, reaching equilibrium within 24 hours from the start of the test. The PC silt experienced equilibrium times between 24 to 48 hours from the beginning of the test. Equilibrium times decreased with each increase of matric suction for the PC silt soil. At low suction values, equilibrium was reached in 48 hours while equilibrium was reached in 24 hours at high suction

values. The Texas clay soil experienced the highest equilibrium times ranging from two to five days from the start of the test. Table 4.12 shows a summary of equilibrium times for each soil type used in the research.

Table 4.12 Equilibrium Times

Soil	Equilibrium Time (hours)
Poorly Graded Sand	<24
PC Silt	24-48
Texas Clay	48-120

From the tests conducted on the three soil types used in the research, the PC silt soil is the recommended soil type for the laboratory module. The PC silt is best suitable for the laboratory module because (1) both Tempe Pressure Cell and Fredlund SWCC devices can be used, (2) the PC silt span a good range of water content values at different matric suction values, and (3) it experienced appropriate equilibrium times. The poorly graded sand had a dramatic drop in water content even at low suction values, and therefore is not adequate for use for the laboratory module. The Texas clay did not experience a decrease in water content until it reached suction values that were too large for the use of the Tempe Pressure Cell device. Also, the Texas clay experienced extremely long equilibrium time that would pose a problem for instructors. Table 4.13 shows the range of soil properties for the soil type recommended for the laboratory module.

Table 4.13 Soil Properties for the Recommended Soil Type

Soil Type	Gradation Type	Specific Gravity	Liquid Limit (LL)	Plastic Index (PI)	% Passing #200 Sieve
Silt	Well Graded	2.73	20-28	3-7	50-60

4.4 Summary

Part of this dissertation was the development of a laboratory module for unsaturated soil mechanics. Two laboratory manuals were created so that the instructor can use either the Tempe pressure cell or the Fredlund SWCC devices. Along with the laboratory manuals, an analysis guide was developed to guide students in constructing the SWCC of the soil using either the empirical Fredlund and Xing (1994) equation or the one-point method using percent passing the #200 sieve and plasticity index (PI) correlations.

An objective of this research was the determination of the best suitable soil type that demonstrated a wide range of matric suction values at different water content measurements while experiencing appropriate equilibrium times. Three different soil types were used in this research, poorly graded sand, PC silt, and the Texas clay. The Fredlund and Xing (1994) equation was used to construct the SWCC for each soil type. Figure 4.10 shows the SWCC for all soils tested. Table 4.12 indicated the equilibrium times for each soil type. Based on the results obtained, a soil with the characteristics of the PC silt is the recommended soil type for use in the laboratory module. Soil properties for the recommended soil type are shown in table 4.13.

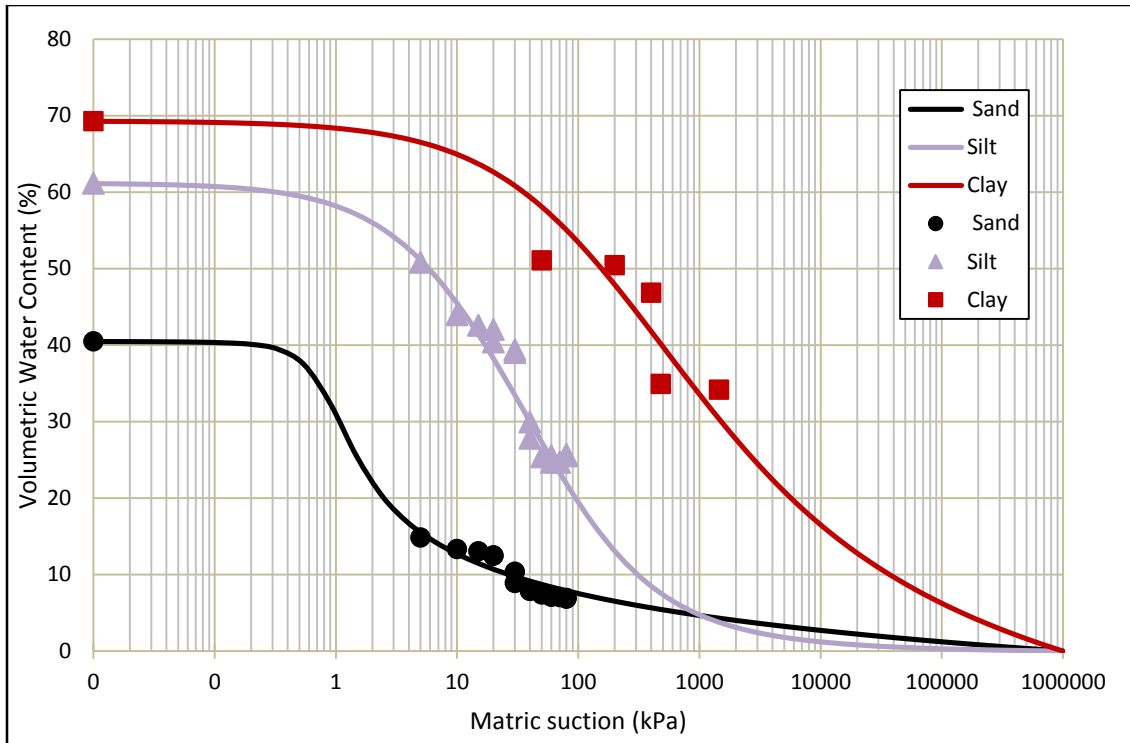


Figure 4.10 SWCC for Each Soil Type Used in the Research

Chapter 5

5 LABORATORY VOLUME CHANGE MEASUREMENTS FROM UNSATURATED TO SATURATED SOIL CONDITIONS

5.1 Introduction

Volume change measurement and analysis for unsaturated soils differs from saturated soils. Saturated soil volume change analysis assumes that the soil is fully saturated (100% saturation) and no air is present in the void spaces. Therefore, the change in volume of the soil specimen is exactly equal to the change in volume of fluid. This differs from unsaturated soil since both water and air occupies the void spaces, and therefore, change in the volume of air must be taken in consideration when assessing soil volume change. Volume change in saturated soils is mostly due to compression (decrease in volume) whereas for unsaturated soils, volume change can arise in the form of shrinkage (decrease in volume) or expansion (increase in volume). Also, unsaturated soils volume change occurs in response to two stress state variables (net normal stress and matric suction), independently; whereas for saturated soils only one stress state variable need be considered, the effective stress. The primary differences in the measurement of volume change for unsaturated soils compared to saturated soils are: (1) changes to any of the two stress state variables, net normal stress or matric suction, can cause a change in volume of the soil, and (2) volume change for unsaturated soils cannot be equated to change in volume of water only.

A transition can be made from unsaturated to saturated soil conditions during laboratory measurement of volume change using the oedometer-type pressure plate device for volume change determination. A traditional consolidation test on a fully

wetted (saturated) specimen can immediately be performed after running the test for determining the wetting SWCC of a soil without having to prepare a new specimen or change testing equipment. This will help capture the transition from unsaturated to saturated condition of soil through laboratory testing, and facilitate implementation of SWCC testing into the traditional undergraduate laboratory experience where consolidation testing is commonly incorporated.

5.2 Test Soil Used for Laboratory Determination of Volume Change for Saturated and Unsaturated Conditions

Only one type of soil was used in order to evaluate volume change properties for saturated and unsaturated conditions, and to demonstrate the transition between unsaturated to saturated soil conditions. The same silt soil from the Price Club construction site in Scottsdale, AZ used in the soil type recommendation for the laboratory module (chapter 4 of this thesis) was also used for the volume change research. The PC silt has liquid limit and plasticity index of 24% and 5%, respectively. The standard Proctor optimum moisture content and maximum dry density for the PC silt are 12.1% and 19.45 kN/m³, respectively. The silt soil was selected because it exhibited some plasticity, and was considered likely to exhibit both acceptable equilibration times for SWCC testing while still demonstrating traditional S-shaped time rate of compression curves for saturated consolidation testing.

5.3 Volume Change for Unsaturated Soils

Volume change for an unsaturated soil can result in either compression (shrinkage) or swelling (expansive). Unlike the saturated condition where all the void spaces are occupied by water, void spaces in the unsaturated soil are occupied by both

water and air. Therefore, volume change is a function of the change in the volume of both water and air. Both water and air are squeezed out of the soil once it is loaded (stressed) either by change in net normal stress or change in soil suction. Volume change does not occur only when loaded by net normal stress but when the moisture content of the soil changes, due to the associated change in the stress matric suction stress state variable. The change of the moisture content (or degree of saturation) can cause the soil to either expand or shrink, thus changing the volume of the soil. For this reason, unsaturated soil cannot be treated the same as saturated soils when it comes to volume change. Different testing methods are needed to analyze volume change, which require control of both net normal stress and matric suction, as well as a means of tracking overall volume change of the specimen.

The constitutive relationships for volume change relate deformation state variables to stress state variables (Fredlund et al., 2012). The constitutive relationship can be graphically presented in the form of the deformation state variable versus two independent stress state variables. Void ratio is commonly used to represent the deformation state of the unsaturated soil, while the net normal stress and matric suction are the controlling stress state variables for unsaturated soils. One-dimensional loading using the Fredlund SWCC device (one-dimensional oedometer pressure plate device) was used to analyze the relationship between deformation and stress state variables as a part of this study.

5.3.1 SWCC Test with Volume Change Measurements

The PC silt was tested using the Fredlund SWCC device to apply one-dimensional loading to the soil specimen at different matric suctions. An electronic dial gauge reader was used to measure the change in the height of the specimen, corresponding to the overall volume change of the specimen. A schematic of the Fredlund SWC-150 device was presented in Figure 4.4.

The testing procedure followed the laboratory manual developed for the laboratory learning module. The soil specimen was compacted at 95% maximum dry unit weight and at optimum water content and placed into the pressure cell. The air pressure was applied to the cell and weights were placed on the load plate to simulate the desired total stress. The initial air pressure was estimated from the SWCC for the PC silt at the optimum moisture content. The air pressure was adjusted so as to maintain the original level of water in the outflow tube, as a method of measurement of the specimen soil suction. This measurement method gives the matric suction at the optimum moisture condition. Once the system reached equilibrium at the initial soil suction, the net normal stress was applied, and equilibration time was allowed at the initial soil suction and the applied net normal stress. During the test, the suction was decreased in stages, with equilibration time allowed at each suction value selected for the SWCC determination. This stress path allowed for the determination of the wetting SWCC curve. Once the specimen reached fully saturation, the suction was increased (drying curve) in increments of 20, 40, 100, 200, 400, 800 and 1200 kPa. Dial gauge readings were recorded at each pressure increment to measure the height of the specimen. This test was done at different

net normal stress of 12.08, 24.16, 48.32 and 96.64 kPa. The data points were used to obtain deformation state variables versus the two independent stress state variables.

5.3.2 Results from the SWCC Test

For each test, the net normal stress was held constant and the matric suction was changed. The test was started by applying the desired stress on the specimen and adjusting the matric suction until the water levels on the Fredlund SWC-150 device reached its original water level. Once the water level reached its original position, the matric suction at this point corresponded to that at the optimum water content and a dial gauge reading was taken to determine the void ratio at this point. Then the suction was decreased and the system allowed to reach equilibrium, the dial gauge reading was recorded. The step was repeated until the sample reached its fully saturation state (at zero suction). This process allowed for the determination of the wetting curve. After the specimen reached equilibrium at zero suction, the suction was increased and the same process was repeated in order to obtain the drying SWCC curve. Volume change results from each loading test are shown in Table 5.1.

Table 5.1 Measurements during the Development of the SWCC at Different Net Normal Stresses

		Net Normal Stress (kPa)			
		12.08	24.16	48.32	96.64
Matric Suction (kPa)	40	0.4871	0.4838	0.4762	0.4679
	20	0.4875	0.4845	0.4769	0.4691
	0	0.4879	0.4851	0.4783	0.4706
	20	0.4876	0.4848	0.4771	0.4694
	40	0.4869	0.4841	0.4765	0.4682
	100	0.4854	0.4811	0.4735	0.4658
	200	0.4841	0.4798	0.4697	0.4623
	400	0.481	0.4752	0.4647	0.4593
	800	0.4743	0.4684	0.4511	0.4484
	1200	0.4681	0.4613	0.4378	0.4342

Figure 5.1 and 5.2 shows change in void ratio resulting from the change in matric suction under different net normal stress conditions. In Figure 5.1, the matric suction is plotted arithmetically while Figure 5.2 is plotted in terms of the void ratio vs. logarithm of effective stress. Figures 5.1 and 5.2 also illustrate the stress path taken by the specimens. Figures 5.3 and 5.4 show the void ratio at given matric suction values for each net normal stress. Plotting the void ratio versus each of the two stress state variables (net normal stress and matric suction) is helpful in determining which stress state variable has a bigger effect on volume change of an unsaturated soil.

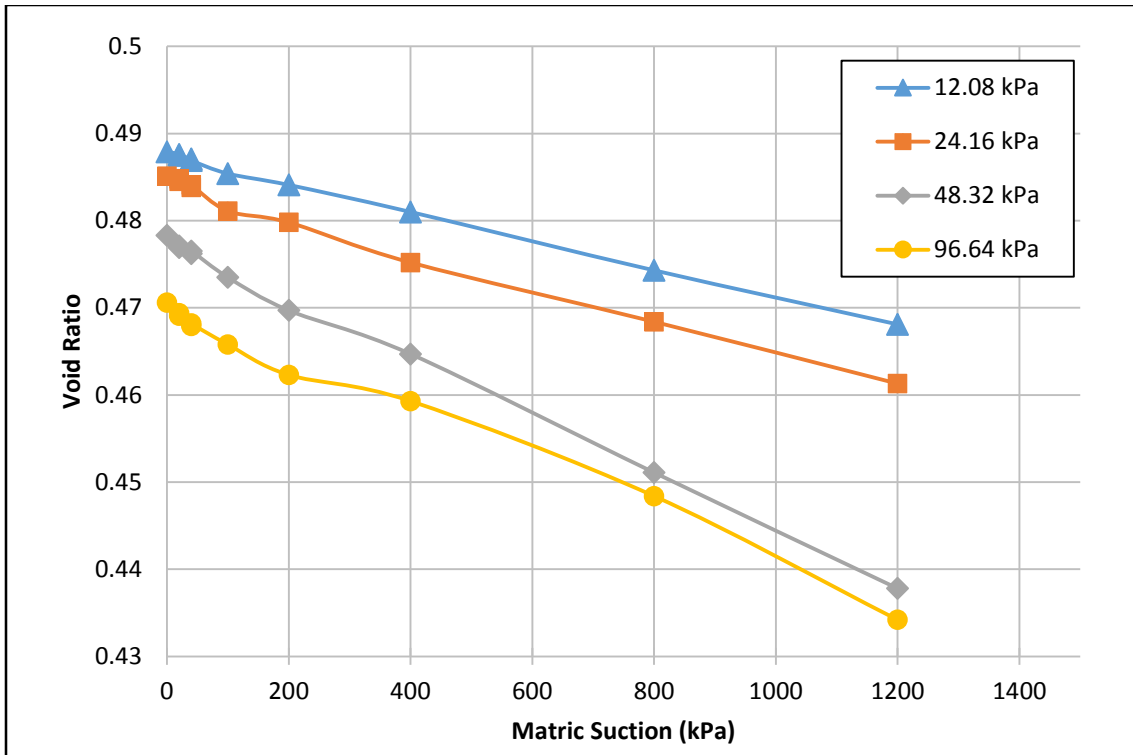


Figure 5.1 Void Ratio vs. Matric Suction for Each Constant Net Normal Stresses

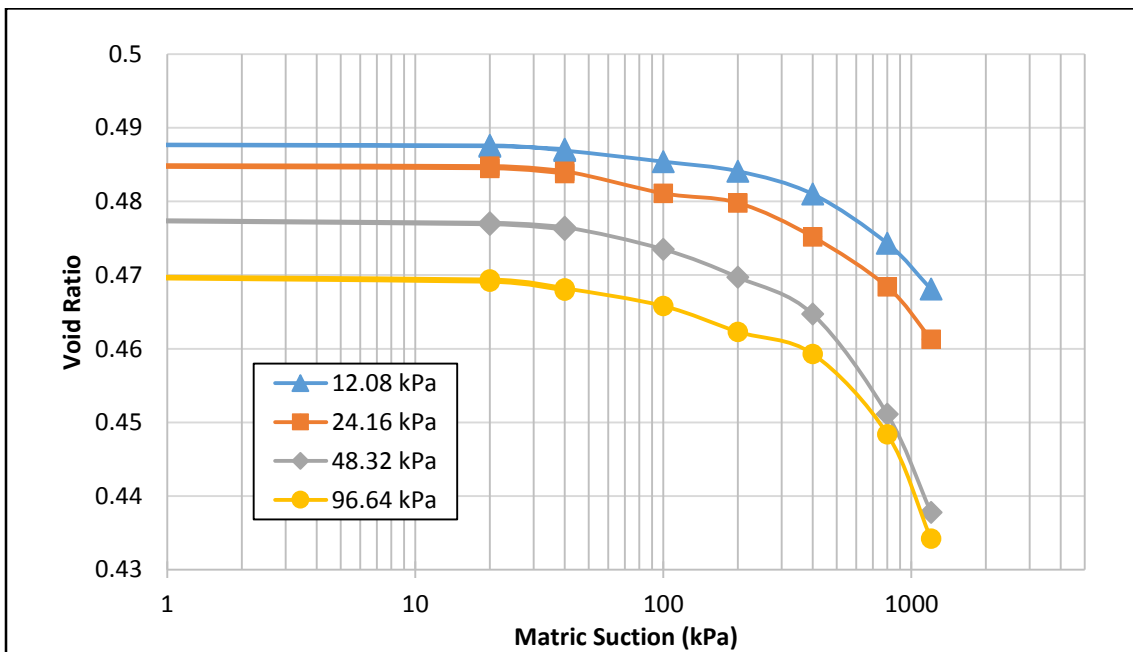


Figure 5.2 Void Ratio vs. Logarithm of Matric Suction

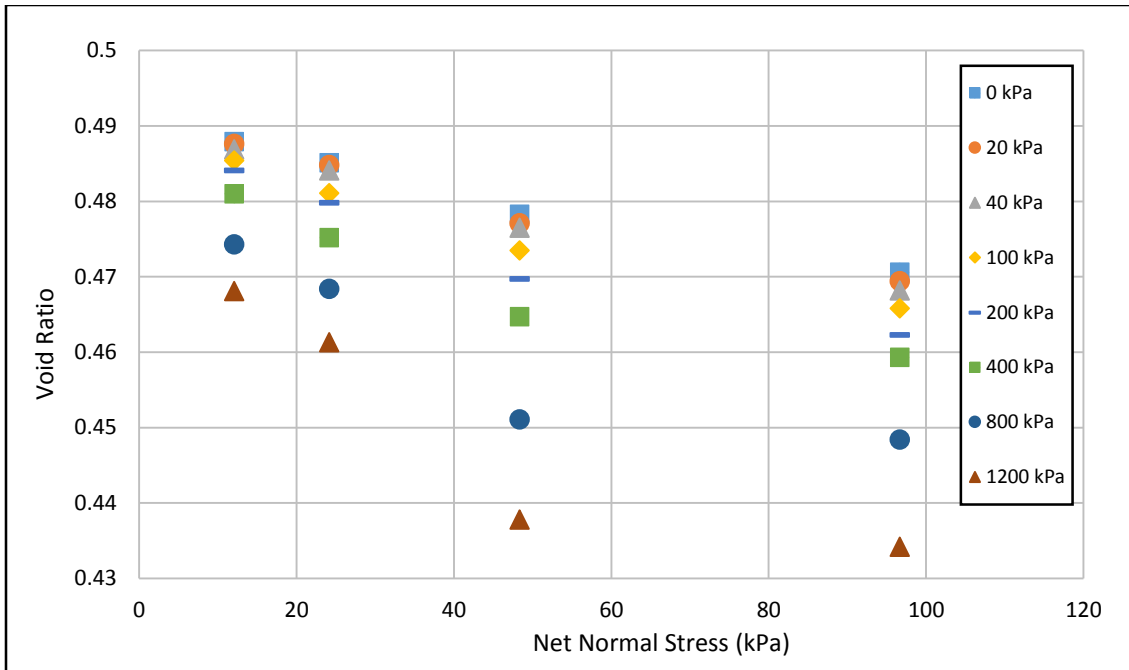


Figure 5.3 Void Ratio vs. Net Normal Stress for Each Constant Matric Suction

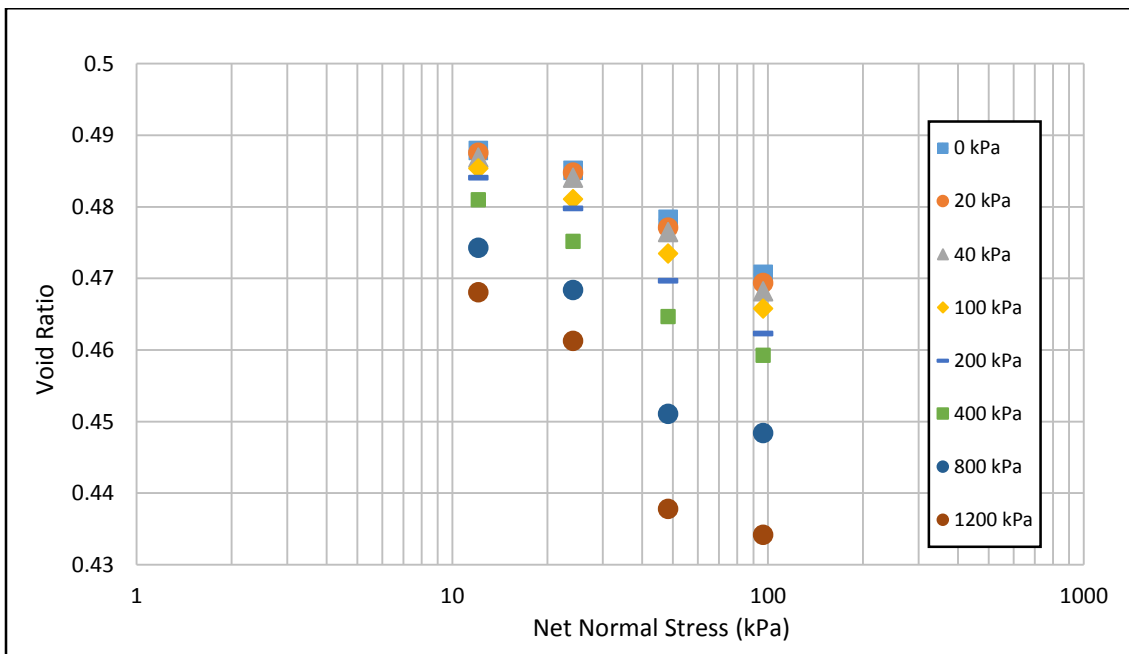


Figure 5.4 Void Ratio vs. Logarithm of net Normal Stress

5.3.3 Effects of Stress State Variables on Volume Change

A study was performed to evaluate the relative impact of net normal stress change and matric suction change on volume change of unsaturated soil specimens. That is, that a given magnitude change in net normal stress will cause greater volume change than the same magnitude change in matric suction. In order to determine if this theory holds true, the effect of each stress state variable on the volume change was examined from the suction tests performed. The compression index for unsaturated soils was used as a tool to compare and determine which stress state variable had a greater impact on volume change. The change in void ratio effected by matric suction is defined as the compression index with respect to matric suction, C_m . The change in void ratio effected by net normal stresses is defined as the compression index with respect to net normal stress, C_t . The compression index with respect to each stress state variable is given by:

$$C_m = \frac{\Delta e}{\Delta \log(u_a - u_w)} \dots\dots\dots (5.1)$$

$$C_t = \frac{\Delta e}{\Delta \log(\sigma - u_a)} \dots\dots\dots (5.2)$$

The compression index was analyzed for each log cycle due to the fact that the slope is non-linear and changes with increasing stress.

In order to estimate the effect of change in matric suction on the void ratio of the specimen, the net normal stress was held constant while the matric suction was allowed to change. Figure 5.2 shows the semi-logarithmic plot of the void ratio at different matric suctions for each constant net normal stress. The compression index with respect to matric suction was used to describe the effect of the matric suction on the void ratio.

Table 5.2 shows the suction compression index values for tests performed at different levels of net normal stress.

In order to estimate the effect of change in net normal stress on the void ratio of the specimen, the matric suction was hold constant, while the net normal stress was allowed to change. Figure 5.4 shows the semi-logarithmic plot of void ratio with respect to net normal stress for each constant suction value. The compression index with respect to net normal stress was used to describe the effect the net normal stress has on the void ratio. Table 5.2 shows the compression index values due to changes in net normal stress for tests performed at different levels of matric suction. By comparing the compression index for each stress state variable, the net normal stress yielded a greater compression index than matric suction for each log cycle.

The ratio of the compression index with respect net normal stress to the compression index with respect to matric suction was analyzed and shown in Table 5.2. The compression index with respect to net normal stress was about 2.7 times greater than the compression index with respect to matric suction at low stress levels of 0.1 to 10 kPa. The ratio increased to 5.2 at a higher stress levels of 10 to 100 kPa. These comparisons show that the net normal stress had a dramatic effect on the volume change compared to an equal magnitude change in matric suction, demonstrating the importance of consideration of the two stress state variables independently.

Table 5.2 Compression Index for Unsaturated Soil Specimens

	Log Cycle		
	0.1-1	1-10	10-100
C_m	0.0004	0.0008	0.0038
C_t	0.0011	0.0021	0.0196
C_t/C_m	2.7	2.6	5.2

5.4. Traditional Consolidation Test on Oedometer-Type Pressure Plate Device

Two consolidation tests using the Fredlund SWC-150 device were performed to determine if the traditional consolidation test could be performed on an oedometer-type pressure plate device. For each test, the specimen was compacted at 95% dry maximum dry density and at its optimum moisture content. A 1-bar ceramic stone disk was used for the test to insure that the drainage of the soil specimen during the consolidation test would not have been impeded by the ceramic stone disk. The test specimen was placed inside the cell and air pressure was applied to the specimen. The pressure was adjusted until the water level on the Fredlund SWC-150 devices was back to its original level. This pressure corresponded to the matric suction at the optimum moisture content. Dial gauge reading were also taken for volume change analysis. Then the pressure was decreased in increments, following the wetting curve, until the specimen reached fully saturation at zero pressure (zero matric suction). Once the specimen reached its fully saturation state, the traditional consolidation test was performed on the same device.

5.4.1 Consolidation Test on Oedometer-Type Pressure Plate Data

The time rate curve is the time versus deformation readings obtained from each load increment as the test progresses. From the consolidation test using the Fredlund SWC-150 device, a time rate curve was obtained for each load increments for the two tests performed. Figures 5.5 through 5.12 are the time rate curves obtained from the two tests. The void ratio and the coefficients of consolidation can be determined from the time rate curves for each of the two tests. It can be observed that the traditional S-shaped curve is obtained for the PC silt, which means that this soil type is appropriate for both SWCC testing and traditional consolidation testing. Therefore, instructors may choose to use a silt soil for both test, perhaps using the same specimen in going from unsaturated to saturated soil conditions.

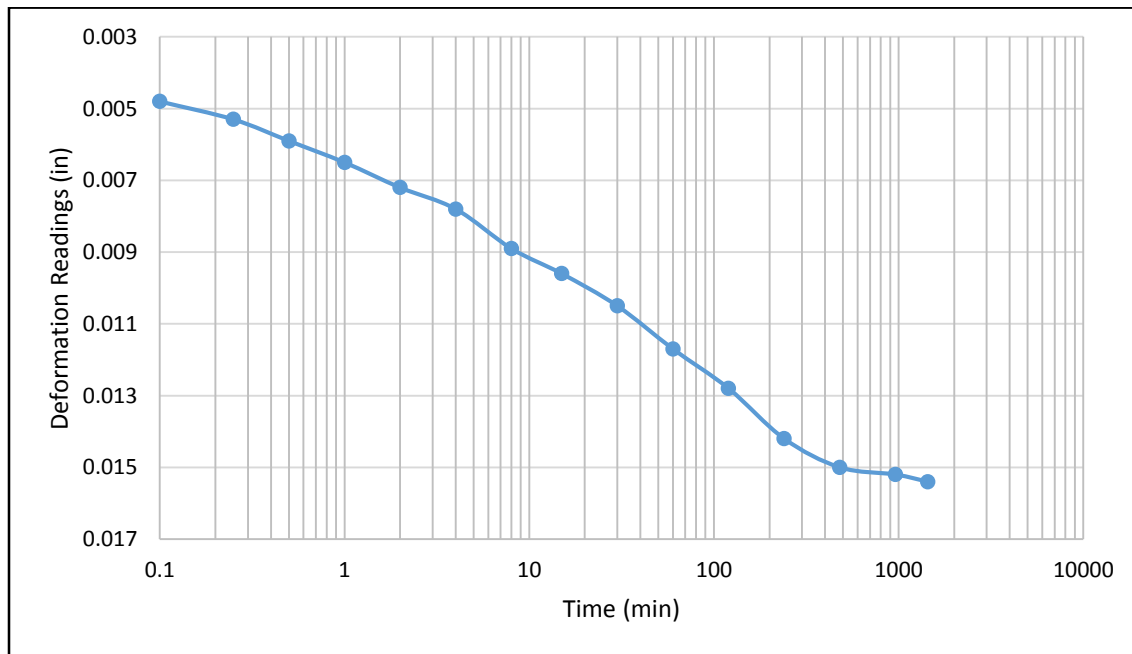


Figure 5.5 Time Rate Curve for Test #1 at 12.08 kPa

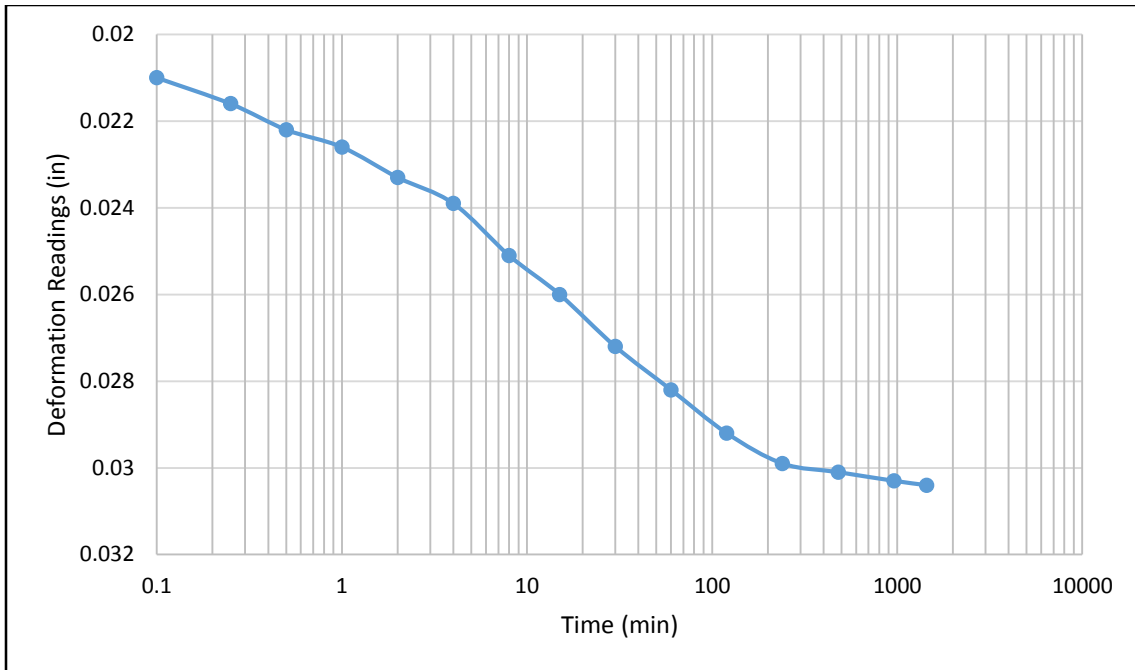


Figure 5.6 Time Rate Curve for Test #1 at 24.16 kPa

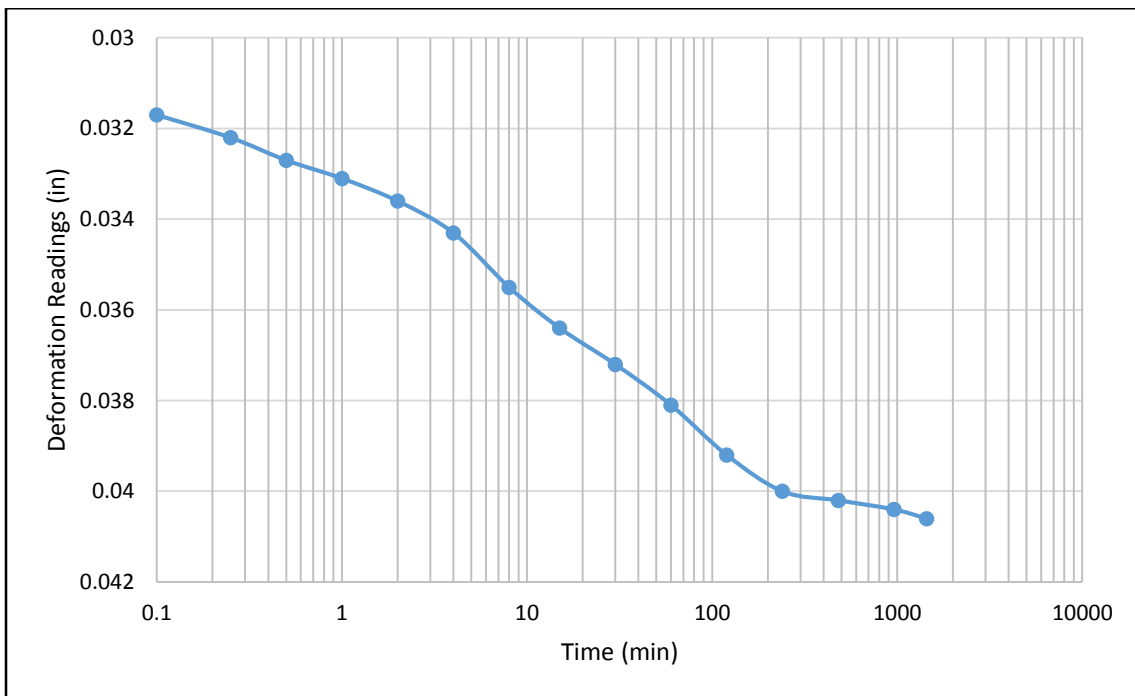


Figure 5.7 Time Rate Curve for Test #1 at 48.32 kPa

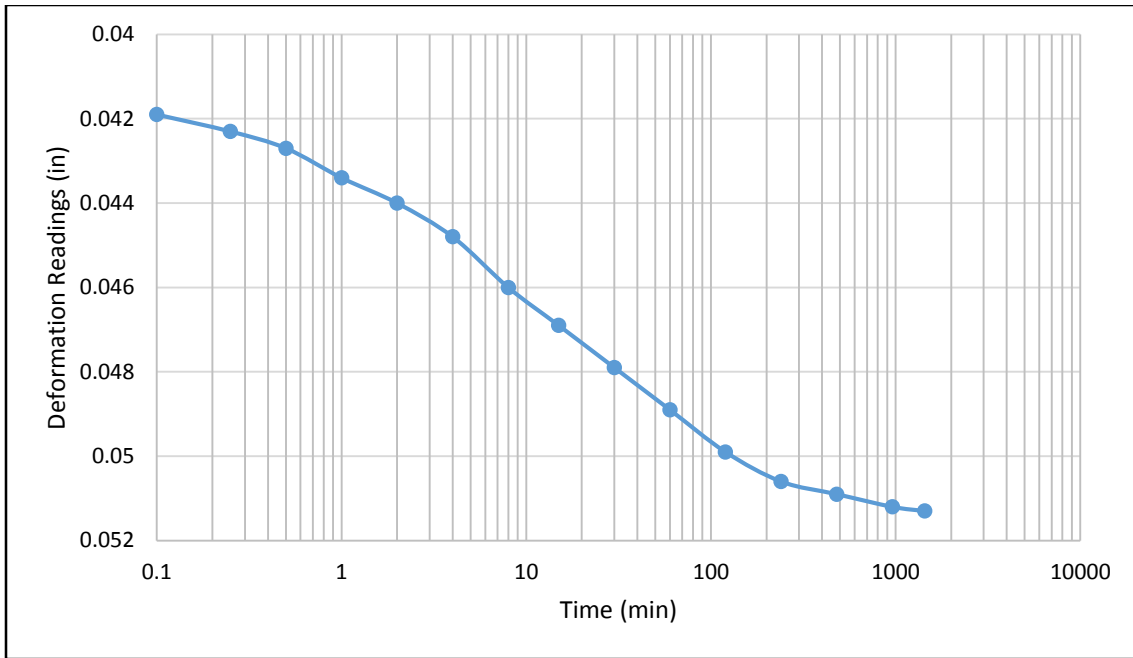


Figure 5.8 Time Rate Curve for Test #1 at 96.64 kPa

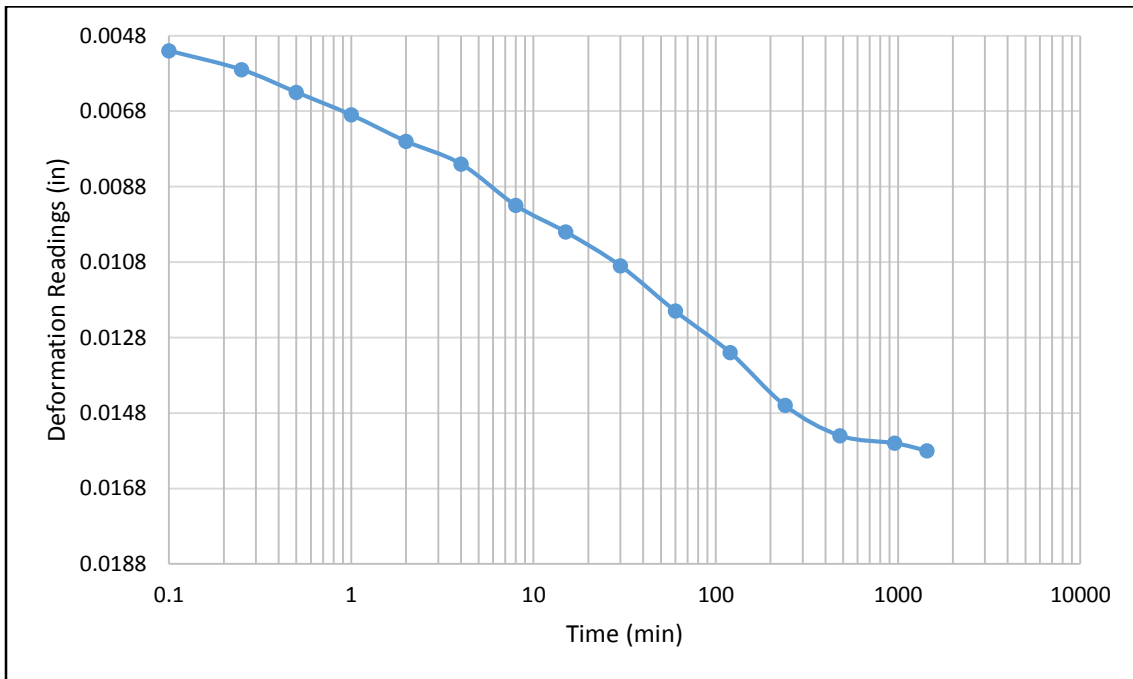


Figure 5.9 Time Rate Curve for Test #2 at 12.08 kPa

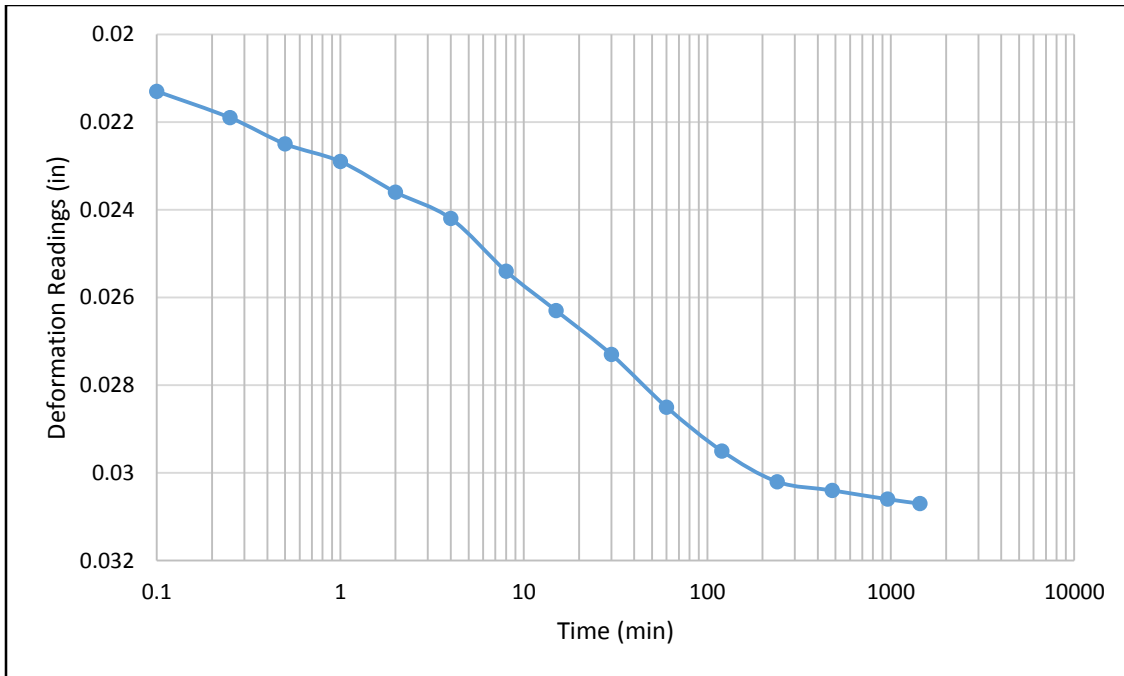


Figure 5.10 Time Rate Curve for Test #2 at 24.16 kPa

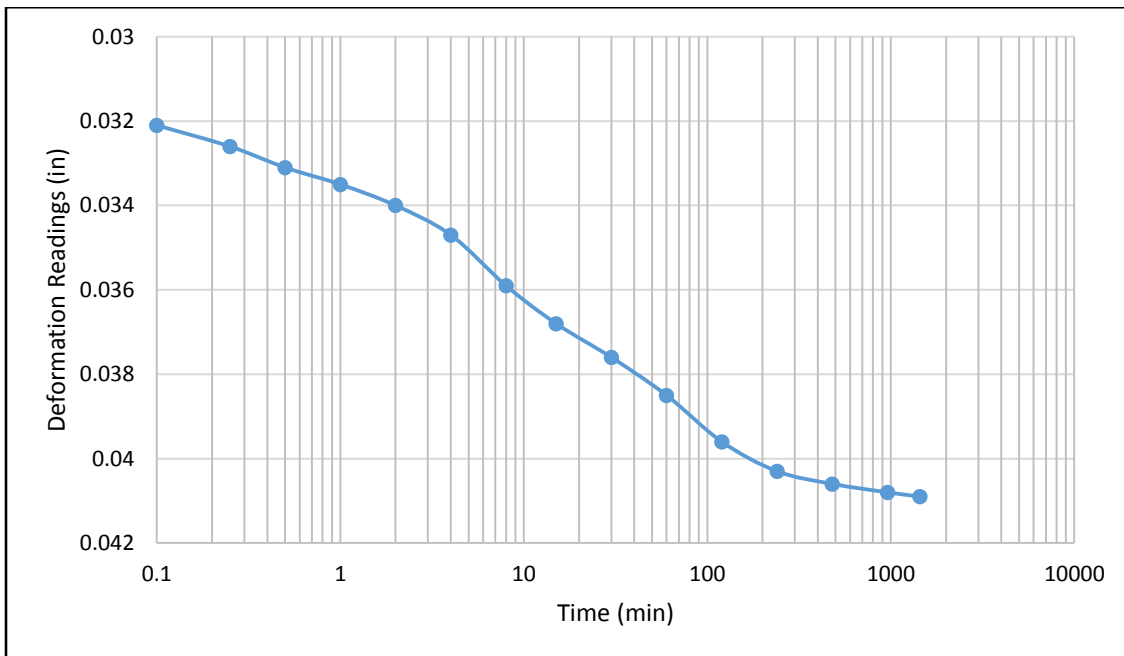


Figure 5.11 Time Rate Curve for Test #2 at 48.32 kPa

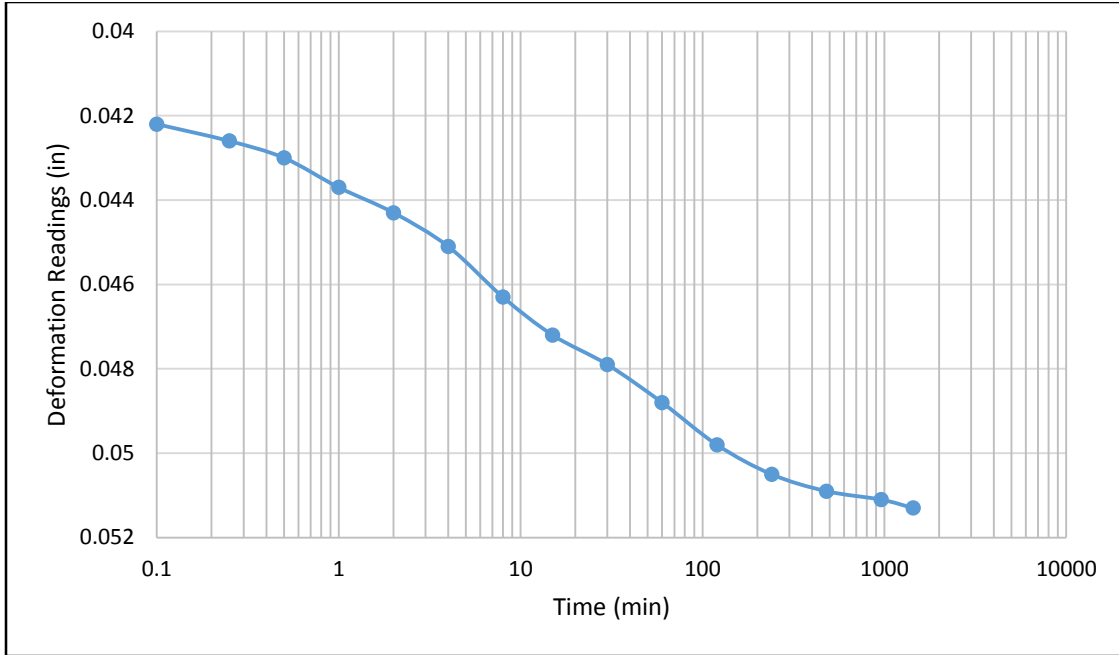


Figure 5.12 Time Rate Curve for Test #2 at 96.64 kPa

5.4.2 Consolidation Test on Oedometer-Type Pressure Plate Results

Table 5.3 shows the final void ratio test results for each oedometer type pressure plate test. Notice that the table starts at 40 and finishes at 96.64 kPa. The values 40, 20, and 0 corresponds with the air pressure (matric suction) applied to the specimen. The values 12.08 to 96.64 kPa corresponds to the stress applied to the specimen at zero air pressure. From the data obtained, a consolidation curve was constructed and can be seen in figures 5.13 and 5.14. The consolidation curve in Figure 5.13 is plotted arithmetically while Figure 5.15 is plotted in terms of the void ratio versus logarithm of effective stress.

Table 5.3 Traditional Consolidation Test Results using the Fredlund SWC-150 Device

	Void Ratio	
$(\sigma - u_w)$ (kPa)	Test 1	Test 2
0	0.4911	0.4886
12.08	0.4904	0.4879
24.16	0.4896	0.4871
48.32	0.4863	0.4838
96.64	0.4746	0.4722

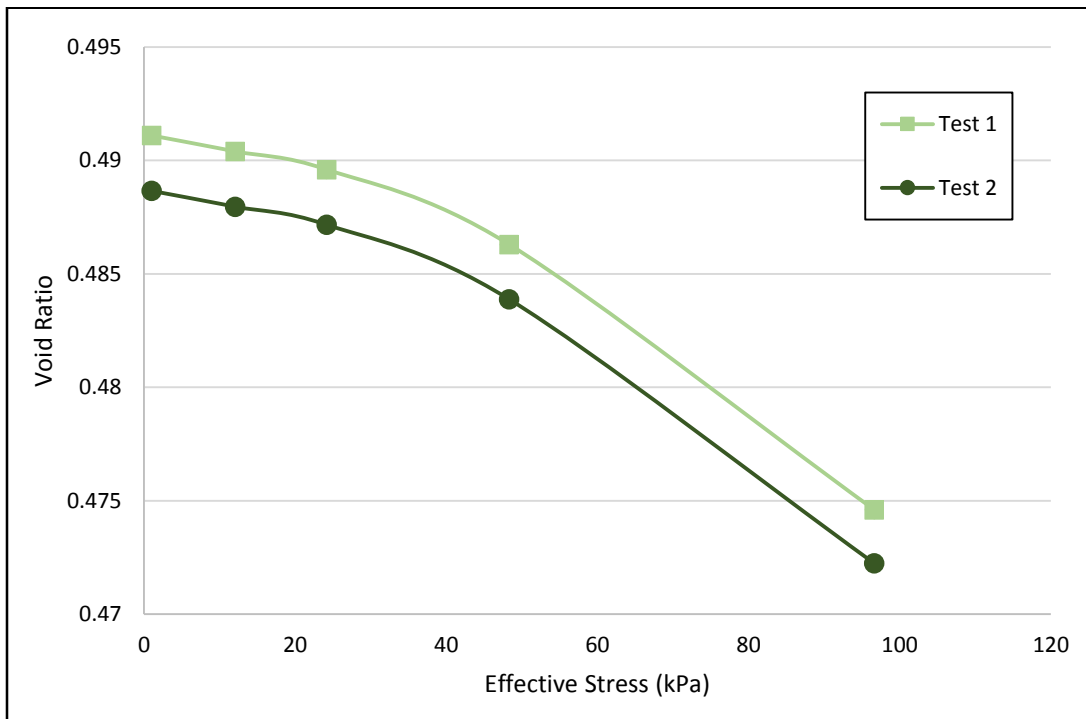


Figure 5.13 Consolidation Curve using Fredlund SWC-150 Device

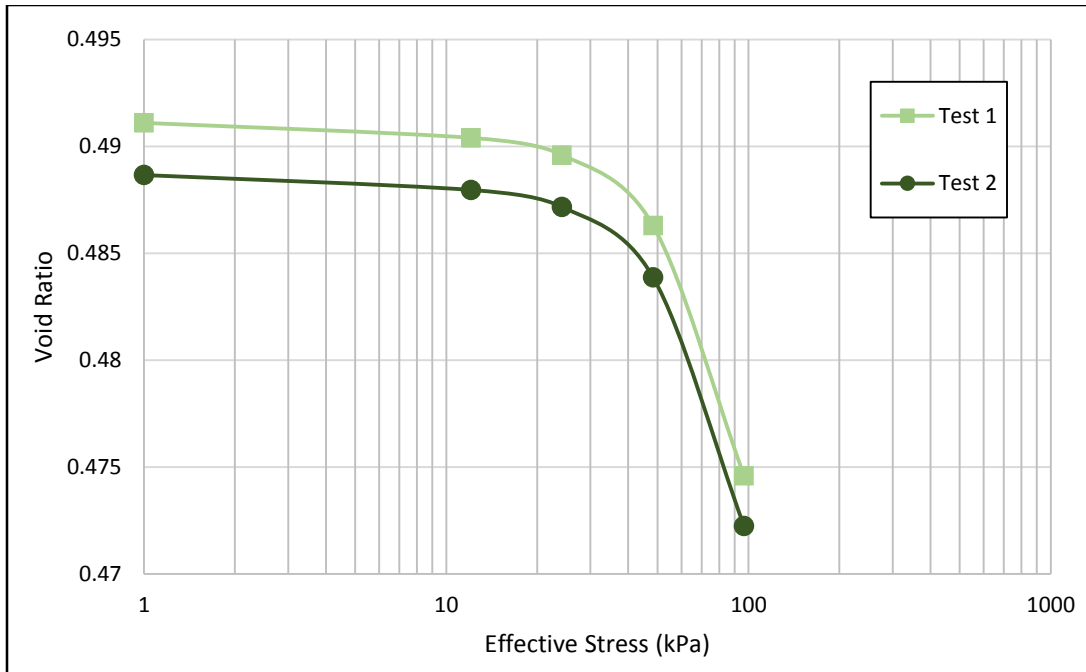


Figure 5.14 Consolidation Curve using the Fredlund SWC-150 Device Presented in a Semi-Log Plot

5.5 Volume Change for Saturated Soils

Saturated soils do generally compress when loaded or stressed. For settlement problems, the soil is assumed to be 100% saturated. For settlement to occur, the pore fluid must be squeezed out of the pores. As the pore fluid is being squeezed out, the soil grains rearrange themselves into a more stable and denser configuration, and a decrease in volume and surface settlement results (Holtz et al., 2011). The compression of the soil when loaded is considered to be one-dimensional. To simulate one-dimensional compression in the laboratory, a consolidation test is performed in a consolidometer device.

5.5.1 Traditional Consolidation Test using the Consolidometer

The consolidation test was completed in accordance to the ASTM D 2435 standard using a fixed-ring consolidometer. The soil was compacted at 95% maximum dry density at optimum moisture content into the consolidation ring. The consolidation ring was then placed into the consolidometer and water was added to saturate the sample. Next, the consolidometer was placed into a loading device and a vertical deflection dial gauge was attached to the top of the loading plate of the consolidometer to measure the compression of the soil. Then the soil specimen was loaded by increments as specified in the ASTM D 2435 standard. The standard loading schedule consisted of approximately 12, 24, 48, 96, etc. kPa (250, 500, 1000, 2000, 4000, etc. lbf/ft²). After each stress increment, the soil specimen was consolidated until it reached equilibrium with little or no further deformation. The process was then repeated for each stress increment. The consolidation test provides data points for the stress-strain plot.

5.5.2 Traditional Consolidation Test Data

The time rate curve is the time versus deformation readings obtained from each load increment as the test progresses. From the traditional consolidation test using the consolidometer, time rate curves were obtained for each load increment. Figures 5.15 through 5.18 present the time rate curves obtained from the consolidation test. The void ratio and the coefficients of consolidation can be determined from the time rate curves for the traditional consolidation test.

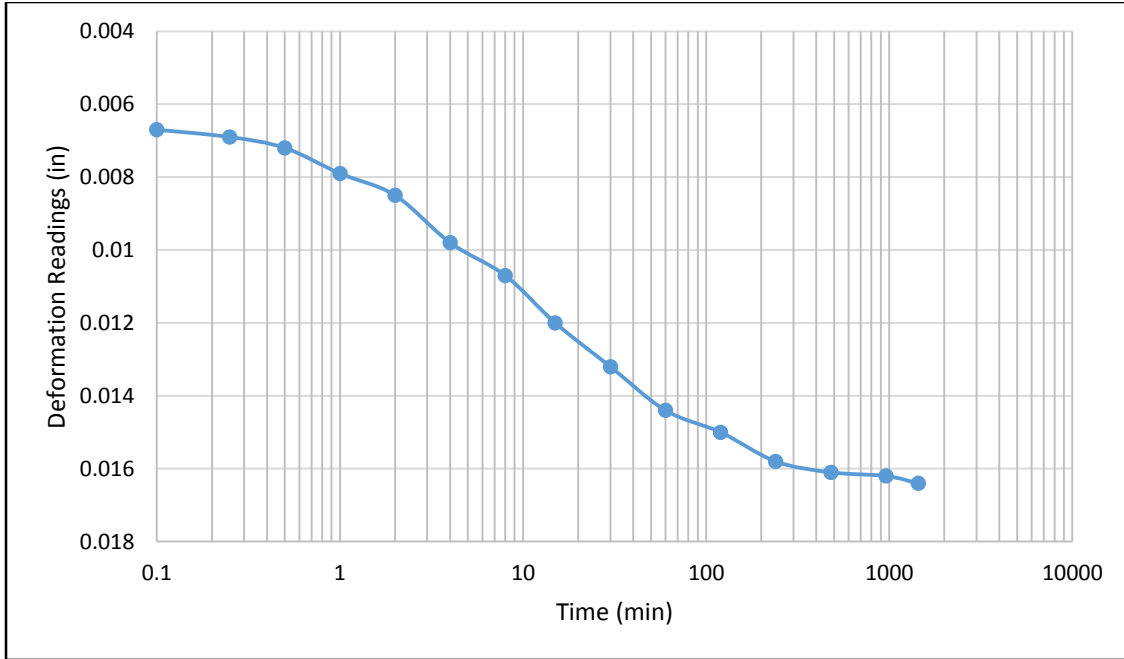


Figure 5.15 Time Rate Curve for the Consolidation Test at 12.08 kPa

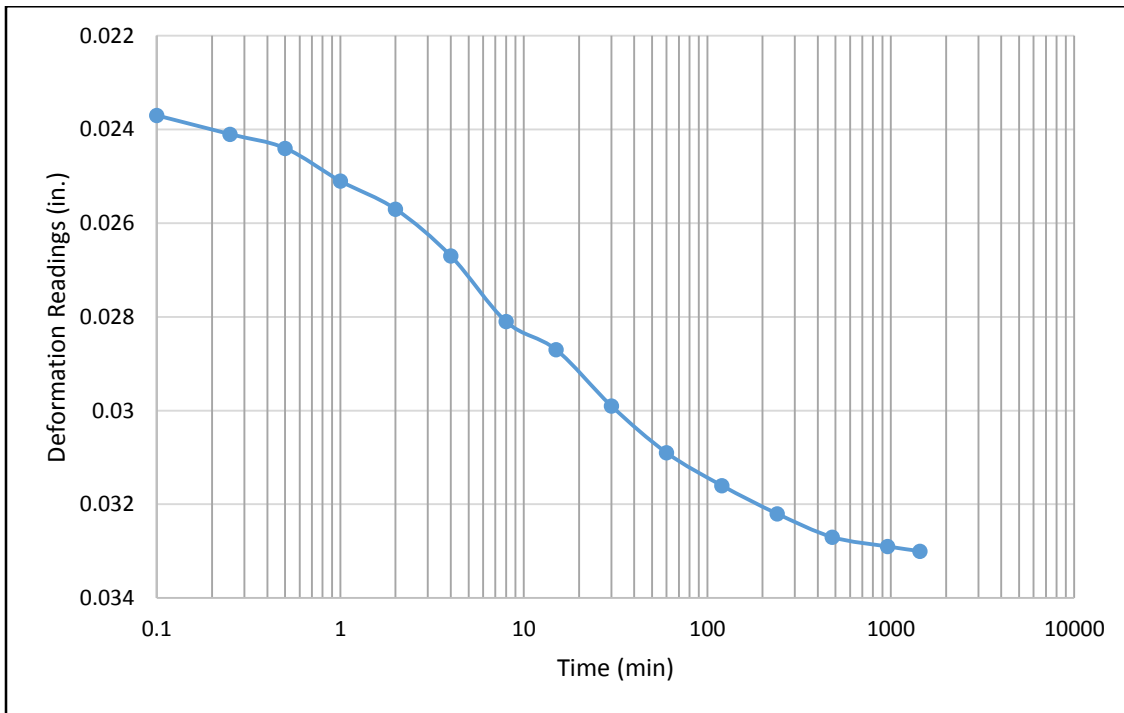


Figure 5.16 Time Rate Curve for the Consolidation Test at 24.16 kPa

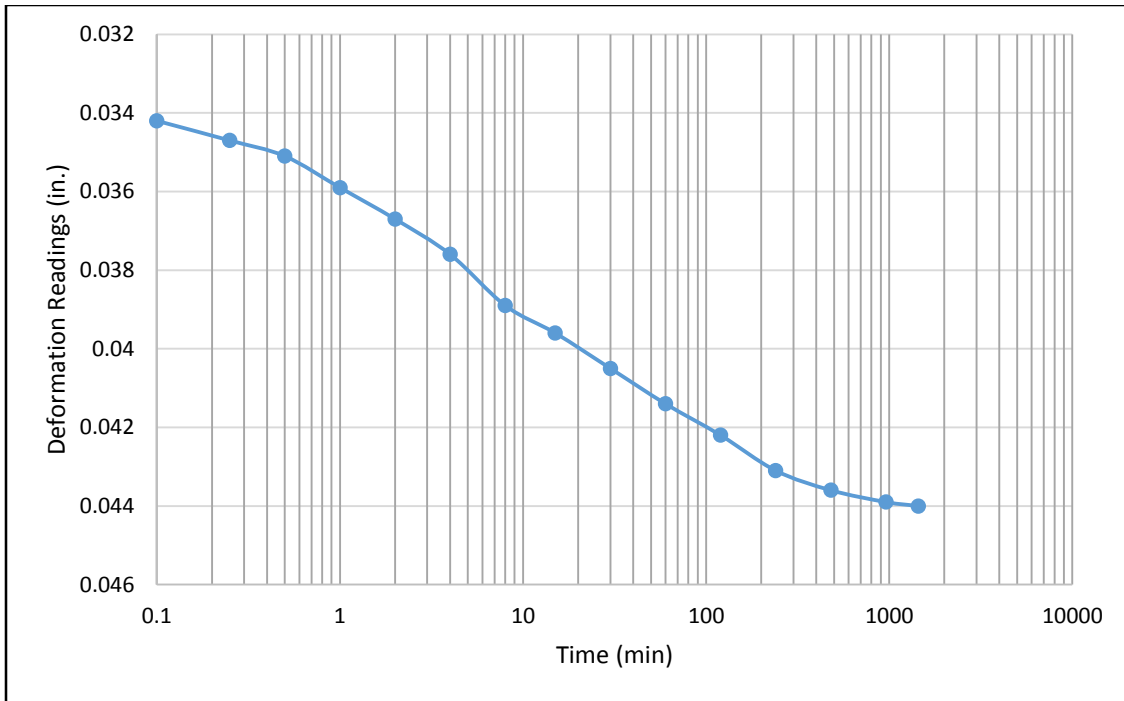


Figure 5.17 Time Rate Curve for the Consolidation Test at 48.32 kPa

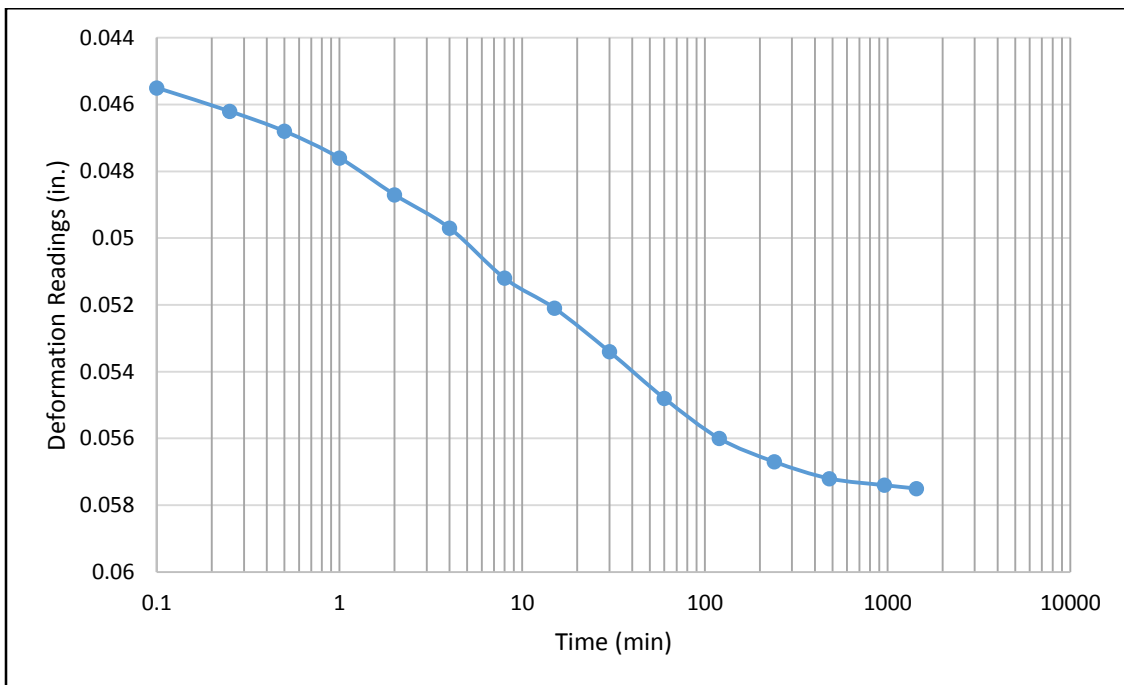


Figure 5.18 Time Rate Curve for the Consolidation Test at 96.64 kPa

5.5.3 Results from the Traditional Consolidation Test

A consolidation curve was developed from the consolidation test. The stress increments used for the test were 12, 24, 48 and 96 kPa, which are the same stress increments used for the volume change results obtained from the Fredlund SWC-150 device. This plot is referred to as the e-log p curve, which is the relationship between the void ratio, and log scaled effective stress (as saturated conditions apply). Table 5.4 shows the data points obtained from the consolidation test on the PC silt soil. From the data obtained, a consolidation curve was constructed and can be seen in figures 5.19 and 5.20. The effective stress in Figure 5.19 is plotted arithmetically while the plot in Figure 5.20 presents the logarithm of effective stress.

Table 5.4 Data Test Results from the Traditional Consolidation Test

$(\sigma - u_w)$ (kPa)	Void Ratio
12.08	0.4825
24.16	0.4795
48.32	0.4742
96.64	0.4608

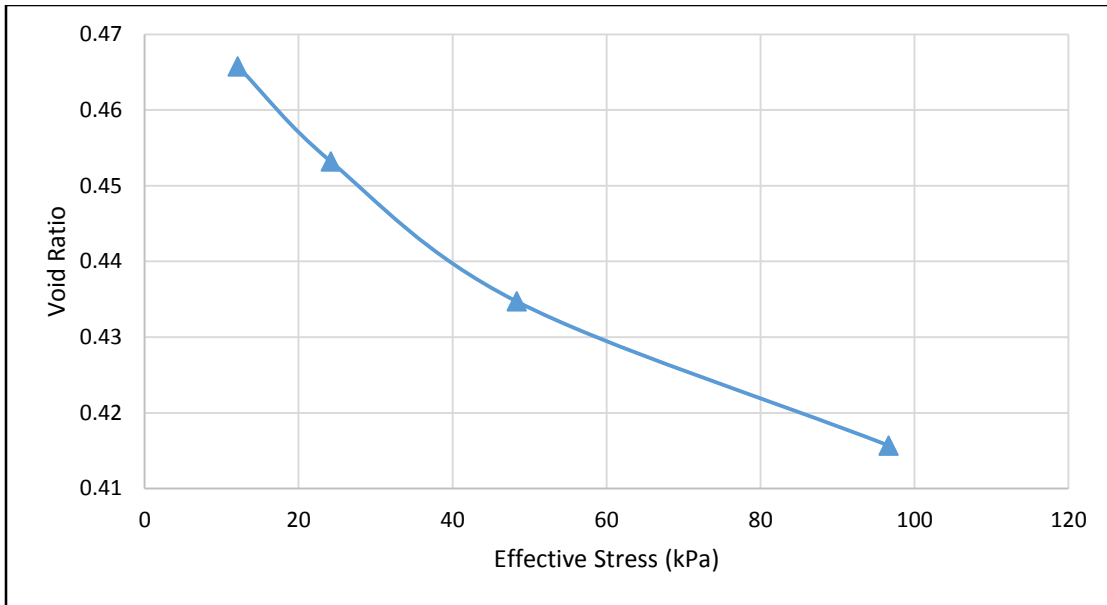


Figure 5.19 Consolidation Curve (Void Ratio vs. Effective Stress)

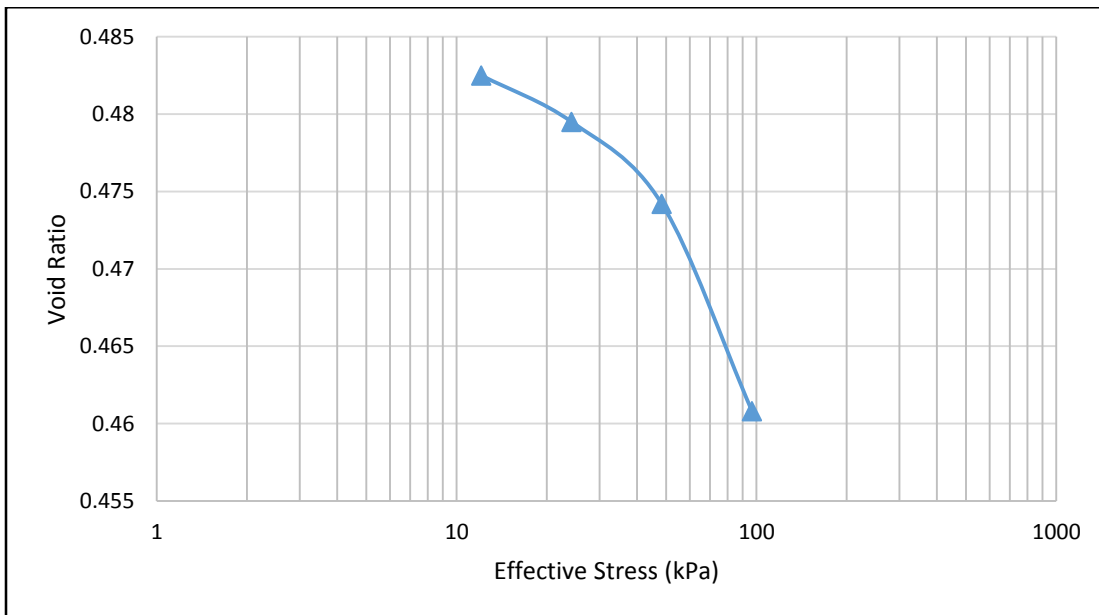


Figure 5.20 Consolidation Curve Presented in a Semi-Log Plot

5.6 Traditional Consolidation vs. Compression Test Using Oedometer-Type Pressure Plate Device

A comparison of the results from the traditional consolidation test and the two consolidation tests performed on the Fredlund SWC-150 device, can be made to demonstrate that an oedometer-type pressure plate device can be used to implement a traditional consolidation test after determining the SWCC of the soil of interest. In order to accomplish this objective, the curves were plotted on the same graph (as seen in Figure 5.21) to compare the two different testing equipment. From the test results, the Fredlund SWC-150 device experienced lower void ratio changes than the consolidometer. The difference is minimal but it is worth considering possible explanations for the differences. One reason is that the stress path taken in the specimen for test 1 and 2 is different than the stress path in the specimen for the traditional consolidation test. The specimens in tests 1 and 2 started at a matric suction corresponding to its optimal moisture content and the specimens were wetted until they reached its full saturation state. Once the specimens reached their fully saturated state, the consolidation test was performed. In other words, the two specimens experienced some sort of a stress prior to consolidation, which resulted in a different initial void ratio when compared to the traditional consolidation test. This also accounts for the change in void ratio. The specimens in tests 1 and 2 demonstrated a lower change in void ratio than the traditional consolidation test.

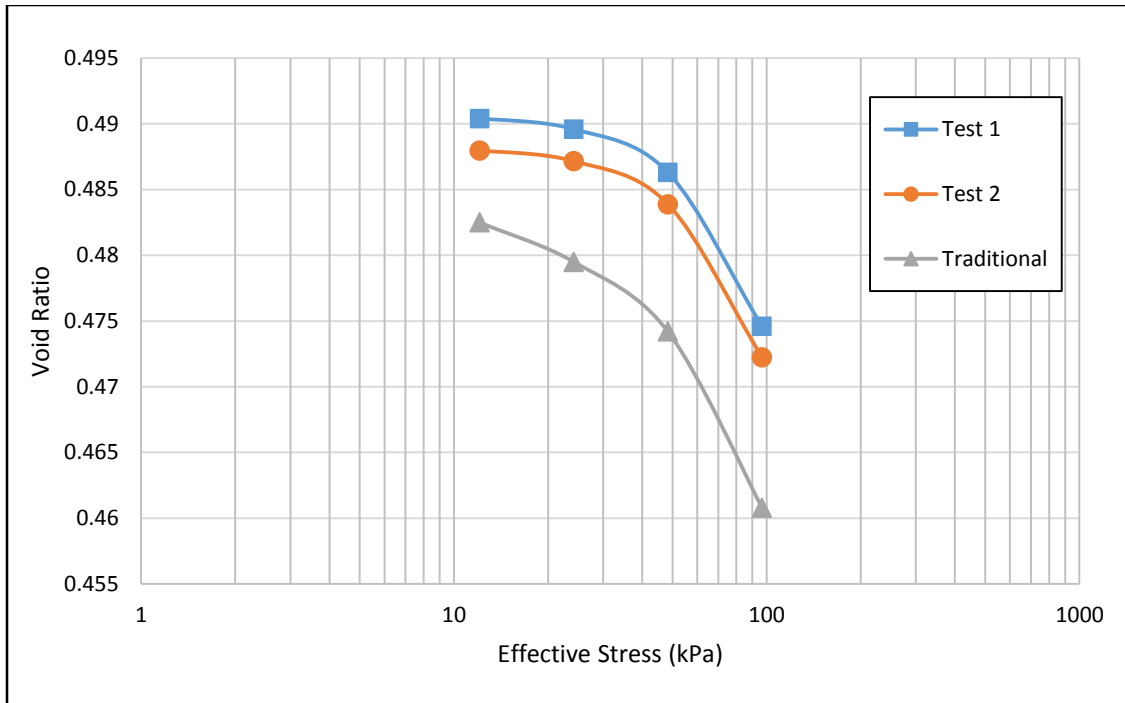


Figure 5.21 Traditional Consolidation Curve vs. Compression Curve using Fredlund SWC-150 Device

5.6.1 Time Rate of Consolidation Comparison

Comparing the coefficient of consolidation was needed to determine if the Fredlund SWC-150 device is applicable to run the traditional consolidation test. The coefficient of consolidation, c_v , is the rate of consolidation and it governs the consolidation process. Using a soil that does not have a low coefficient of consolidation is an important parameter to incorporate volume change analysis using the Fredlund SWC-150 device.

The results of the coefficients of consolidation using the PC silt soil can be seen in Table 5.5 for the traditional consolidation test and the two consolidation tests performed using the Fredlund SWC-150 device. The coefficient of consolidation was

plotted to visualize the results as seen in Figure 5.22. The graph shows the coefficient of consolidation versus logarithm pressure (effective stress and net normal stress). The traditional consolidation test and the consolidation test performed on the Fredlund SWC-150 have similar coefficients of consolidation. The coefficients of consolidation are high enough to conduct compression tests in laboratory to perform volume change analysis using a silt type soil.

Table 5.5 Coefficient of Consolidation

$(\sigma - u_w)$ (kPa)	c_v of Traditional Consolidation Test ($10^{-3} \text{ m}^2/\text{day}$)	c_v of Fredlund SWC-150	
		Test #1 ($10^{-3} \text{ m}^2/\text{day}$)	Test #2 ($10^{-3} \text{ m}^2/\text{day}$)
12.08	2.23	3.09	2.97
24.16	3.90	4.52	4.30
48.32	5.46	5.89	5.68
96.64	7.74	8.83	8.56

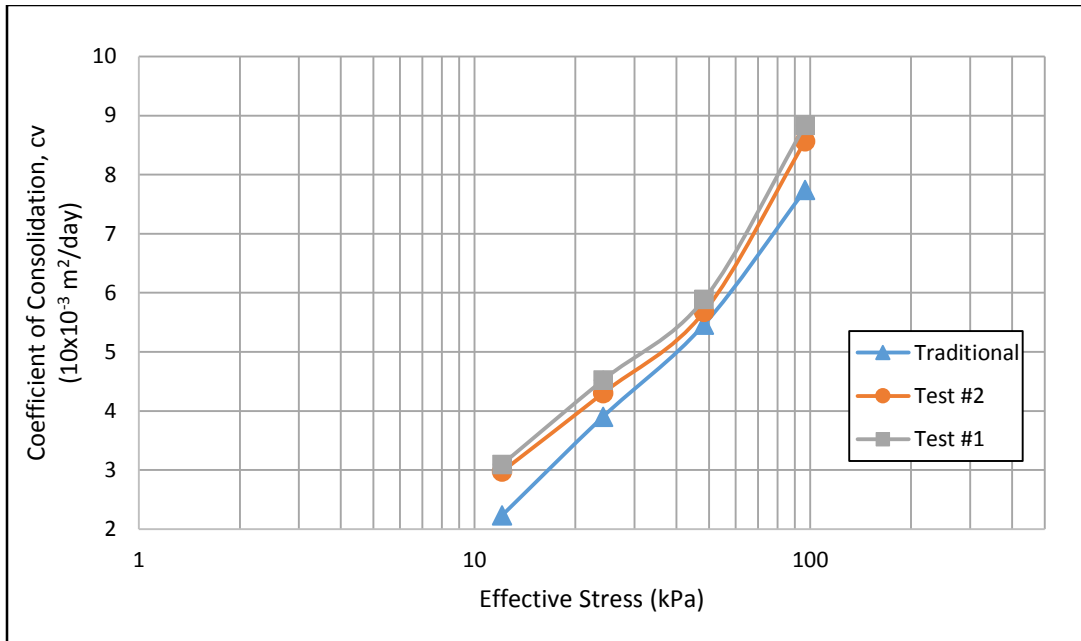


Figure 5.22 Coefficient of Consolidation vs. logarithm of Effective Stress

5.7 Impedance Drainage Check for the High-Air Entry Ceramic Stone Disks

Since the Fredlund SWC-150 device contains a high-air entry ceramic stone disk at the bottom of the soil specimen, impedance drainage needed to be considered. This means that the HAE ceramic disk might slow down the dissipation of pore pressure of the soil specimen. The total volume change will be the same but the rate of consolidation might change due to the impedance of the HAE ceramic disk. The impedance drainage factor, also called retardation, was determined to figure out if the high-air entry ceramic disks affected the rate of consolidation of the test specimen during consolidation using the Fredlund SWC-150 device.

The impedance factor is defined as:

$$R = \frac{k_2 H_1}{k_1 H_2} \dots\dots\dots (5.3)$$

Where k_1 is the hydraulic conductivity of the soil specimen, k_2 is the hydraulic conductivity of the HAE disk, H_1 height of the soil specimen, and H_2 is the height of the HAE disk. The impedance factor is a non-unit parameter. The following criteria are used in order to determine if the ceramic disk impedes drainage of the soil specimen. If:

- $R \geq 100$, then there is no impedance at all.
- $R \geq 50$, then the impedance is negligible.
- $R \geq 30$, then the impedance is negligible for most engineering applications.
- $10 \leq R \leq 30$, then it is borderline impedance and impedance may or may not be negligible.
- $R \leq 10$, then impedance does occur.

Table 5.6 shows the hydraulic conductivity and height of the soil specimen and each of the HAE ceramic disks used for the Fredlund SWC-150 device. The hydraulic conductivity of the HAE ceramic disks were provided from the manufacturer of the ceramic stones, SoilMoisture Equipment Corp. The hydraulic conductivity used for this analysis was estimated based on the coefficient of consolidation equation. The coefficient of consolidation equation is defined as:

$$c_v = \frac{k}{\gamma_{water}} \frac{(1+e_o)}{a_v} \dots\dots\dots (5.4)$$

Where:

k = Hydraulic conductivity

γ_{water} = Unit weight of water

e_o = Initial void ratio

a_v = Coefficient of compressibility

The initial void ratio and coefficient of compressibility are obtained from the time rate curves during consolidation tests performed on the Fredlund SWC-150 device. The hydraulic conductivity of the silt soil used for the tests was determined to be 4.8×10^{-9} cm/s. The hydraulic conductivity using the coefficient of consolidation equation is considered to be low compared to typical values of hydraulic conductivity, which are “ 10^{-8} to 10^{-3} cm/s” (Coduto, 1999) for silt soils.

The impedance factor for each HAE ceramic disk is summarized in Table 5.7. From the impedance factor obtained for each ceramic disk, the 1, 3, and 5-bar ceramic disks do not impede the drainage of the soil specimen. However, the 15-bar does impede the drainage and affects the rate of consolidation of the soil specimen during consolidation testing. Using the 3 and 5-bar ceramic stone disks would have been acceptable to use during the consolidation test performed on the Fredlund SWC-150 device.

Table 5.6 Hydraulic Conductivity and Height of Soil Specimen and HAE Disks

	Hydraulic Conductivity (cm/s)	Thickness (cm)
Silt	2.8E-09	2.53
1-bar	7.6E-07	0.714
3-bar	2.5E-07	0.714
5-bar	1.2E-07	0.714
15-bar	2.6E-09	0.714

Table 5.7 Impedance Factor for HAE Disks

HAE Disk	Impedance Factor	Impedance Factor Criteria
1-bar	268	No impedance
3-bar	88	Negligible impedance
5-bar	43	Negligible impedance
15-bar	0.92	Impedance

5.8 Unsaturated to Saturated Condition Transition

An oedometer-type pressure plate device was used to demonstrate the transition from unsaturated to saturated state conditions for a soil test specimen in the determination of volume change. A soil specimen was tested at a constant net normal stress while adjusting the matric suction to obtain a full SWCC curve with volume change measurements. Then the matric suction was set to zero and allowed the specimen to reach equilibrium. The soil specimen reached its full saturation state once the specimen reached equilibrium. The consolidation test was then performed on the same soil specimen and device.

The test results obtained from the unsaturated compression tests and the traditional consolidation tests were plotted in a three-dimensional plot. The plot consists of the relationship of void ratio, matric suction, and net normal stress and is shown in Figure 5.23. On the three-dimensional plot, the limiting plane (shaded in blue in Figure 5.23) is when the matric suction is zero and this is considered to be the saturated condition. At zero matric suction, the net normal stress becomes the effective stress only

when pore water pressures are zero and the pore air pressure is atmospheric (zero). Understanding this transition, the traditional consolidation curve is positioned on the limiting plane of the three-dimensional void ratio constitutive surface – that is, the shaded limiting plane on Figure 5.23 is the void ratio versus effective stress plot shown previously in Figure 5.19. Thus, Figure 5.23 shows the plot of the transition from unsaturated to saturated condition.

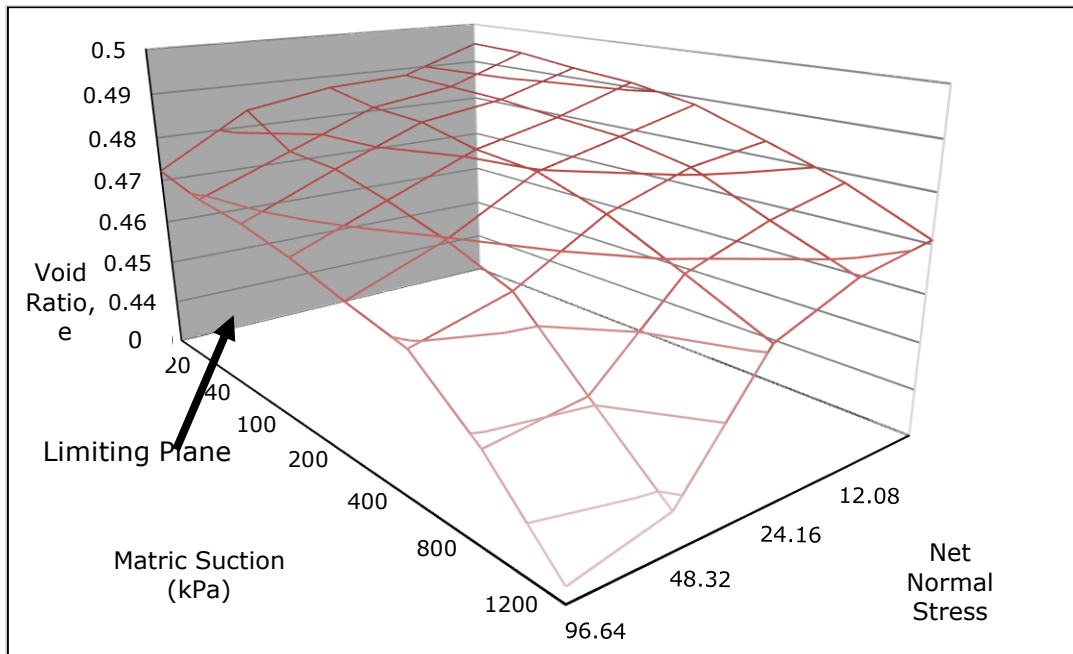


Figure 5.23 Three-dimensional Void Ratio Constitutive Surface

Soil-water characteristic curves were also obtained using the SWC-150 device where volume change measurements were obtained during SWCC testing. A SWCC for each net normal stress was developed and plotted in a three-dimensional graph as shown in Figure 5.24. The degree of saturation was used for the water measurement of the test specimens because it is commonly used in engineering practice, and because it takes into consideration volume change. The plot in Figure 5.24 demonstrates the relationship of

degree of saturation, matric suction, and net normal stress. The degree of saturation is effectively 100% at zero suction. A change in either stress state variable (suction or net normal stress) causes change in the degree of saturation of each test specimen – a decrease for increasing net normal stress and increasing matric suction. Therefore, changes in either stress state variable effect the degree of saturation of the test specimens, and this is reflected in the plot of Figure 5.24. Note that the highlighted (shaded) limiting plane of Figure 5.24 is the SWCC curve as performed under zero net normal stress, such as is done when the Tempe cell is used to determine the SWCC of a soil.

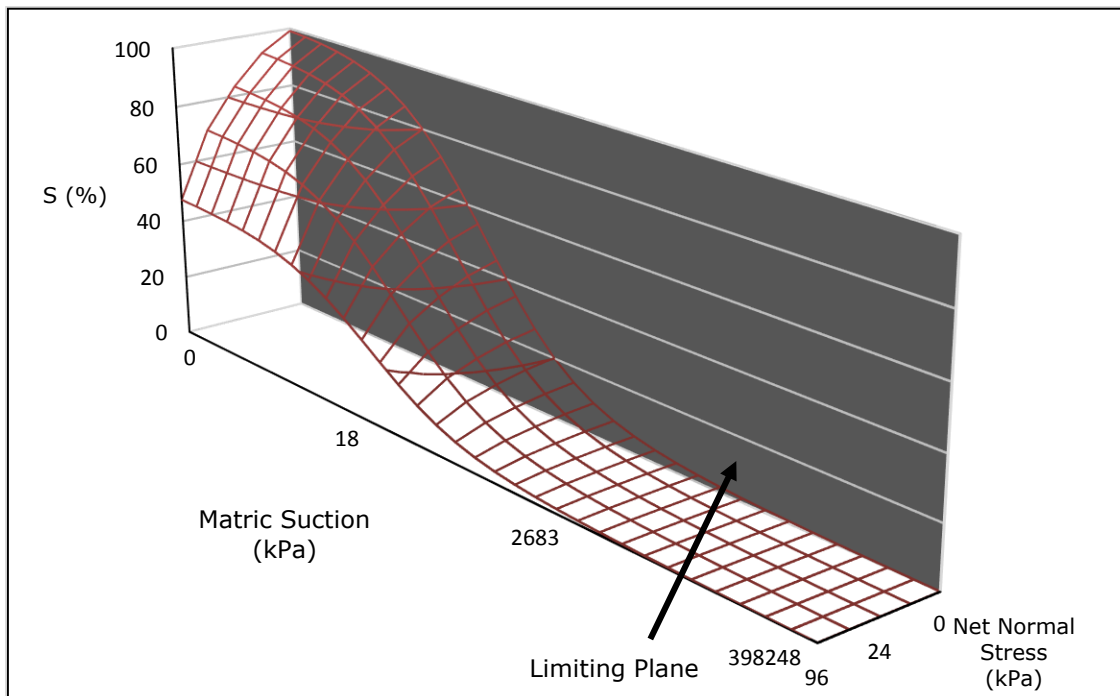


Figure 5.24 Three-dimensional Degree of Saturation Constitutive Surface

Chapter 6

6.0 CONCLUSION

6.1 Summary of Research

The purpose of this research is to introduce unsaturated soil mechanics to the undergraduate geotechnical engineering students as a part of the introductory geotechnical engineering course. The unsaturated soil mechanics teaching material were developed so that it merges smoothly into the current curriculum with sufficient flexibility for broad adaptation by faculty. The learning material consists of three lecture modules and a laboratory module. Along with the unsaturated soil mechanics learning material, a demonstration of transition from unsaturated to saturated soil conditions through volume change laboratory tests was presented, wherein an oedometer type pressure plate device was used for the full range of unsaturated to saturated soil conditions.

6.1.1 Summary of Learning Material

The lecture modules introduced soil mechanics for the general medium condition with the saturated soil as a special case. The basic unsaturated soil mechanics principles were used in each lecture module. The three lecture modules that were developed are (1) the stress state variables for unsaturated soils, (2) soil-water characteristic curve, and (3) axis translation. A PowerPoint presentation was created to present each module to the undergraduate students. Each PowerPoint presentation was presented in easy to understand manner so that the students will enjoy the learning material.

Along with the lecture modules, a laboratory module was developed as part of the learning material for unsaturated soil mechanics. The laboratory module reinforces the important key aspects and concepts for unsaturated soil behavior. Two laboratory manuals were developed for the laboratory testing on unsaturated soils in order for the students to construct their own SWCCs. A laboratory manual was created for the Tempe Pressure Cell and Fredlund SWC-150 device (one-dimensional oedometer pressure plate device) in order to give the instructor and institution a choice of which testing equipment best fits their program. Each laboratory manual consists of a step by step procedure on how to conduct the test and data sheets with tables in order for students to have the necessary laboratory data needed for the SWCC analysis. Along with the laboratory manuals, an analysis guide was created to help students through the analysis in constructing SWCCs. Two different analysis approaches were taken: a nonlinear regression fit analysis using the Fredlund and Xing (1994) equation and the one-point method. It is important for students to know how to use both methods in determine an SWCC of their soil of interest.

A soil type recommendation was also researched for use in the laboratory module. The soil should ensure proper equilibrium times along with a wide range or suction values controlled by both testing equipment (Tempe Pressure Cell and Fredlund SWC-150). Certain soil types can take several days to reach equilibrium during testing which is unacceptable by instructors. An ideal soil's SWCC transition slope should occur between suction values of 40 to 1400 kPa so that both the Tempe Pressure Cell and Fredlund SWC-150 devices could be used for the recommended soil. Three different soil types, poorly graded sand, silt, and clay, were used in determining best suitable soil type. Figure

4.10 shows the SWCCs for each soil type and Table 4.12 indicates the equilibrium times that each soil type experienced during testing. A silt type soil material with similar soil properties of the silt soil used for the research is recommended for the laboratory module. The recommended soil type along with a range of certain soil properties can be seen in Table 4.13.

6.1.2 Transition from Unsaturated to Saturated Condition through Volume Change

Determination

Part of this thesis demonstrated a smooth transition from unsaturated to saturated condition through laboratory volume change experiments using a silt soil tested in an oedometer-type pressure plate. Three different experiments were conducted: (1) volume change for unsaturated soils, (2) volume change for saturated soils using unsaturated soils testing equipment, and (3) traditional consolidation test. The volume change testing for unsaturated soils was performed by running a compression test in the Fredlund SWC-150 device. The volume change for saturated soils, using unsaturated soils testing equipment, was performed by conducting a traditional consolidation test using the Fredlund SWC-150 device. A traditional consolidation test using the consolidometer was performed for traditional volume change tests for the saturated condition.

A comparison from the test results of the consolidation (saturated) test on the Fredlund SWC-150 device and traditional consolidation test performed in a consolidometer was made. Figure 5.21 shows the consolidation curves for all tests. The traditional consolidation experienced a higher change in void ratio than the two consolidation tests performed on the Fredlund SWC-150 device. Also, the time rate of

consolidation for each test was calculated. From these test outcomes, the Fredlund SWC-150 device can be used to conduct traditional consolidation tests, provided a high air entry ceramic stone not higher than 5 bars is used during the test. It appears that a 15-bar stone might create impedance of flow, which will complicate the interpretation of the results and affect the coefficient of consolidation.

From each test, the void ratio versus the stress state variable for each condition was plotted on a three-dimensional graph to visualize the transition from unsaturated to saturated condition which is seen in Figure 5.23. The void ratio for an unsaturated soil is a function of both stress state variables, net normal stress and matric suction. As the soil reaches its fully saturation state, the matric suction is equal to zero and the net normal stress becomes the effective stress for saturated soils, provided atmospheric conditions prevail. From this statement, the volume change for saturated soils lies on the void ratio-net normal stress plane on the three-dimensional plot from Figure 5.23.

Soil-water characteristic curves were also obtained from the same tests performed on volume change. The plot in Figure 5.24 demonstrates the relationship of degree of saturation, matric suction, and net normal stress. The degree of saturation is 100% at zero suction and net normal stresses. Not only does the stress state variables had an effect to the volume change, but it also had an effect to the degree of saturation of the test specimens.

6.2 Implementation Efforts

Once all the lecture and laboratory modules were completed, partner universities across the United States used the material for their undergraduate geotechnical engineering courses. The partner institutions that have used the unsaturated soil

mechanics modules from this research are Arizona State University, University of Texas at Arlington, University of Puerto Rico-Rico at Mayaguez, University of Missouri-Columbia, University of Colorado at Boulder, University of Oklahoma, and Purdue University. Table 6.1 shows when and what learning modules were used by each partner institution for their undergraduate geotechnical engineering course, including the academic time in which they were used. Every partner institution found it difficult to find time to implement the modules into their curriculum. This is the reason why during the Spring semester of 2013; only the stress state variable lecture module was implemented. Only Arizona State University has implemented all three lecture modules and the laboratory module into the curriculum.

Table 6.1 Modules Implemented by Partner Universities

Semester	Modules Used	University
Spring 2013	Stress State Variable Module	<ul style="list-style-type: none"> • The University of Missouri-Columbia • The University of Puerto Rico-Rio Mayaguez • The University of Texas-Arlington • Arizona State University • The University of Colorado-Boulder
Spring 2013	Stress State Variables, SWCC, Axis-Translation, and Laboratory Modules	<ul style="list-style-type: none"> • Arizona State University (Advanced Geotechnical Engineering Course)
Summer 2013	Stress State Variables, SWCC, and Axis-Translation Modules	<ul style="list-style-type: none"> • Arizona State University
Fall 2013	Stress State Variables, SWCC, Axis-Translation, and Laboratory Modules	<ul style="list-style-type: none"> • Arizona State University • The University of Oklahoma • The University of Texas-Arlington • Purdue University

6.3 Modifications Made to Modules

A nine-question survey was created for students to take before and after the lecture modules were presented. These surveys were done in order to establish if the students were learning the basics concepts of the lecture modules and to evaluate the effectiveness of the learning materials being presented to the students. Along with the

survey, students were asked questions to provide feedback on how the modules could be improved. The majority of the feedback suggested that a textbook would be helpful to better understanding the material outside of the classroom. Outside of this request, there was not much improvement needed to be done from the student's standpoint. Many students did comment on how much they enjoyed the modules and that they had a better understanding about unsaturated soil mechanics after taking the lectures. The analysis of the data collected during the pre- and post-surveys is out of the scope of this thesis but it will be presented as a part of a dissertation currently in progress.

Instructors who have used the lecture modules provided valuable feedback about the modules. The feedback indicated some minor changes or adjustments were needed to be done on the PowerPoint slides such as spelling errors, improvement on certain figures, and format enhancing. Each module was modified based on the feedback and reevaluated in order to improve the content. In addition, some PowerPoint slides were adjusted to better clarify certain concepts. For example, in the Stress State Variable module, there was some confusion about the sandcastle example. To address this issue, adjustments were made to better clarify the purpose of the example in a way that students could better understand the concept.

The laboratory manuals have been revised based on the feedback from the Advanced Geotechnical Engineering class at Arizona State University. Some minor spelling and grammar errors were corrected. The most important issue that the students experienced is the confusion during the testing procedure. Many of them had problems following the procedure and made some suggestions on how to improve the documents. These suggestions were implemented to better clarify certain steps in the procedure of the

laboratory testing and to minimize any confusion it may arise in future use of the laboratory manuals. Another problem that commonly occurred was the analysis for constructing SWCCs using the Fredlund & Xing (1994) equation. Some adjustments were made in the analysis guide to provide key resolutions for problems that may transpire while using the Excel[®] program.

6.4 Interdisciplinary Interaction Experience

Working with members of the Educational Technology program at Arizona State University on this research served as a tremendous experience. The members include Dr. Wilhemina Savenye, professor in the Mary Lou Fulton Teachers College; and Arthur Ornelas, John Sadauskas, and Allen Corral, doctoral students in the Educational Technology program. Their expertise greatly improved the PowerPoint presentations for each lecture module by making them more effective and efficient for students to learn the material. One of the best experiences learned from working with the educational technology members was the ability to work in teams and the importance of communication. Communication in a group setting is vital in accomplishing the main objective that everyone is working towards. Being able to communicate what important learning material should be implemented in the PowerPoint slides was key for them to relay the information to the students in a better to understand manner through the PowerPoint presentation.

The Educational Technology members were fundamental in the development of surveys for students to take before and after they were presented with the lecture modules. The objective of the surveys was to determine if the modules were effective in transferring knowledge and also identifying what concepts were being understood and/or

misunderstood. At the time of the writing of this thesis, Mr. Ornelas and Mr. Corral were in the process of analyzing the survey data to understand what the students learned and what important material was not comprehended. Also, several questions apart from the survey were developed to get feedback from students on how the modules could be improved. Based on the feedback, changes were made to modules. Having the Education students analyzing the survey data was very important in order to determine what changes were needed to enhance student learning.

Being the only research assistant on the engineering side of the research was sometimes difficult. There was a lot of work that was put into developing figures and equations, laboratory manuals, and soil type recommendations. Having another person to work and collaborate with on a daily basis would have been more effective and productive. Even though it was difficult at times, being able to manage different tasks at the same time will be very useful out in the work force. Also, working as a team was beneficial as an engineer and will serve as a tremendous skill to have when practicing as an engineer since most projects involve teamwork. Working with everyone on the research was a tremendous learning experience that will never be forgotten.

6.5 Recommendations on Additional Modules

The modules developed thus far do not represent sufficient material to cover all of the unsaturated soil mechanics principles. Volume change and shear strength are two important subjects that should be developed in the additional modules. Most engineering problems involve volume change and the strength of the soil. Measuring volume change during the laboratory module should also be incorporated into the laboratory module. This will pair very well with the recommended volume change lecture module.

Volume change is usually introduced as soil compressibility in the undergraduate geotechnical engineering course. Volume change of the soil is represented as a change in void ratio but sometimes represented as vertical strain. For saturated soils, volume change is conventionally shown as a function of effective stress. Compressibility for unsaturated soils should be presented by both volume change versus change in net normal stress for a constant suction and volume change versus matric suction for a constant suction. A discussion on how volume change can be positive (expansion) or negative (compression) depending on the change of the stress state variables. Students should be able to understand the response of the volume change when one or both stress state variables are changing. Simple examples of each change to the stress state variables should be included in the module. Understanding volume change is a very effective tool to acquire for engineering practice.

Shear strength of the soil is very important parameter required in the design of several geotechnical engineering structures, particularly in slope stability analyses. Many slope stability problems occur when there is a change in moisture content of the soil. Understanding the change in shear strength of a soil material is a key aspect that would impact the stability of many slope problems. There should be discussion of the effect of a change of either stress state variables on the shear strength of the soil. There should also be a mention of the numerous shear strength equations that have been proposed for predicting the shear strength versus suction relationship for unsaturated soils (Fredlund, Sheng, & Zhou, 2011).

Incorporating volume change into the laboratory module will pair very well with the volume change lecture. Measuring volume change in the laboratory would not be too

difficult to do. Only minor adjustments will be needed in the laboratory manuals such as additional steps in the procedure and additional tables in the data sheets. The only big obstacle with incorporating the volume change is that the Tempe Pressure Cell cannot be used. The instructor must have a one-dimensional oedometer-type pressure plate device to be able to measure the volume change of the soil specimen. Students will plot the relationship of the void ratio versus net normal stress at constant matric suction and void ratio versus matric suction at a constant net normal stress.

6.6 Ways to Enhance Learning

Aside of the modules developed for unsaturated soil mechanics; there should be additional material available to students to use. Some additional material should include textbooks or packets of relevant material, lecture videos, and laboratory videos. It is difficult for students to grasp on the concepts when only being exposed to it once. It will be helpful if the students had options on using additional material outside of the classroom.

A textbook about unsaturated soil mechanics will be very useful as a reference that students can go back and utilize to better understand the concepts presented in the lecture modules. Even though textbooks could be very helpful, it can also be costly. If a textbook is not a good option for certain students, then packets of relevant material discussed in the modules can be used.

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APPENDIX A

STRESS STATE VARIABLES LECTURE POWERPOINT PRESENTATION

State of Stress in Soils

Lecture

Arizona State University

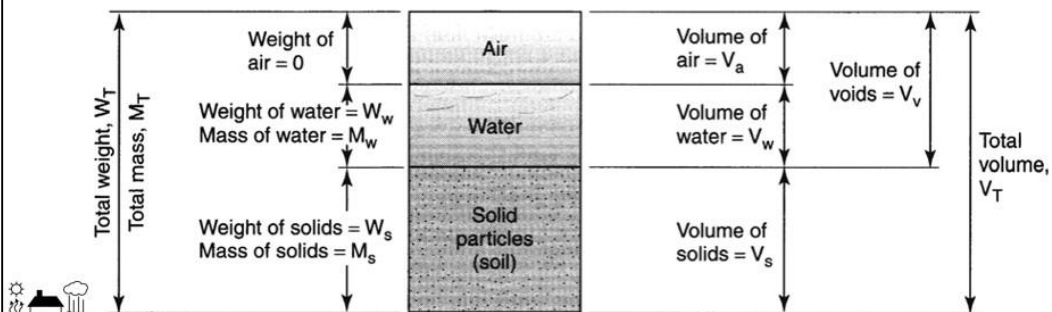


UNSATURATED SOILS

Soil Phases

In general, soil has three (3) phases:

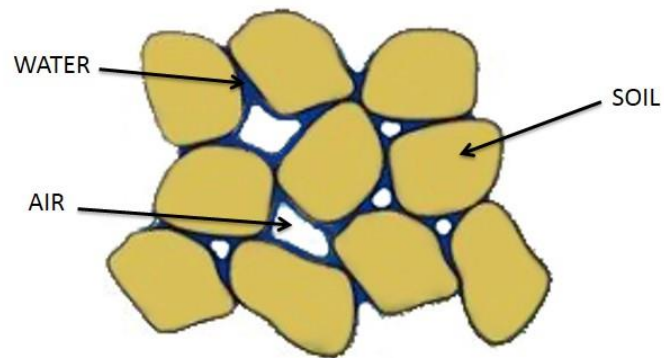
1. Solid soil particles
2. Water
3. Air



UNSATURATED SOILS

Saturated vs. Unsaturated

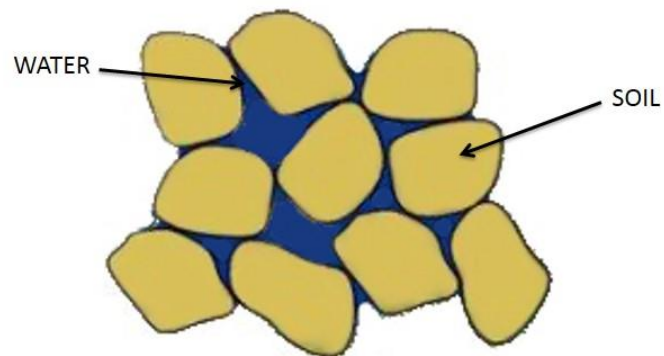
When both air and water occupy the void space between particles, the soil is **unsaturated**.



UNSATURATED SOILS

Saturated vs. Unsaturated

When the void space is filled with water the soil is **saturated**.



UNSATURATED SOILS

Scope of This Module

This module covers the stress state of soils. We will:

- begin with the most general case of unsaturated soil (with all three phases present).
- progress to special cases, including the special case of saturated soil.



UNSATURATED SOILS

State of Stress in Soils

What is Stress?

- In its simplest form, stress is defined as:
Force/Unit Area

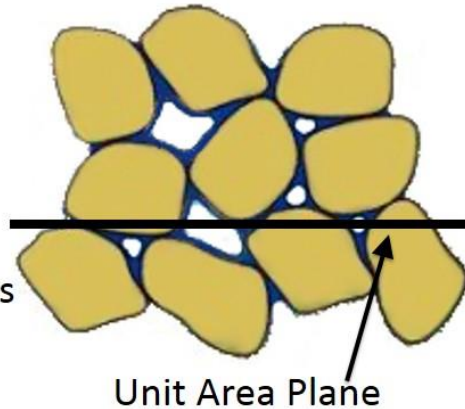


UNSATURATED SOILS

State of Stress in Soils

What is the Unit Area?

- In the application of soil mechanics, it is the gross cross-sectional area that is used in defining stress.
- This means the Unit Area represents a plane that cuts across solid soil particles, the voids between them, and anything in the voids.



UNSATURATED SOILS

Why Use Gross Cross-Sectional Area in Defining Stress?

- For many geotechnical engineering applications (particularly foundation design) it is necessary to identify **measurable** stress state variables that control the soil's deformation and shear strength.
- Referencing to the soil gross cross-sectional area facilitates the measurement of stress.



UNSATURATED SOILS

Why Use Gross Cross-Sectional Area in Defining Stress?

- Referencing to the soil gross cross-sectional area is also equivalent to treating the soil as a continuous medium.
- Sometimes this is referred to as taking a **macro-level** approach.



UNSATURATED SOILS

What Forces Act on Soils?

Both **external** and **internal** forces act on soils.



UNSATURATED SOILS

What Forces Act on Soils?

External Forces

- The combined weight of the soil and structures on it are examples of external forces.
- These forces, distributed over the unit area, result in what is called **total stress**: $\sigma = F/A$.



UNSATURATED SOILS

What Forces Act on Soils?

Internal Forces

- Internal forces arise from two internal pressures or stresses:
 - pore water pressure (u_w)
 - pore air pressure (u_a)



UNSATURATED SOILS

State of Stress of Soils

Because soil is, in general, a 3-phase medium (air, water, and solid), there are 3 stresses that must be considered in describing the overall state of soil stress:

1. total stress (σ)

- normally compressive

2. pore air pressure (u_a)

- normally positive or zero

3. pore water pressure (u_w)

- can be positive or negative, but is normally negative when the soil is unsaturated and all three phases (solid, water, and air) are present

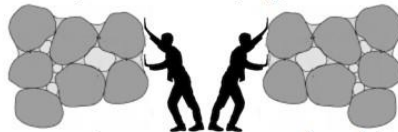


UNSATURATED SOILS

State of Stress for Unsaturated Soil

- Total normal stress (σ) tends to push grains together.

- Positive pore air pressure (u_a) tends to push grains apart.



- Negative pore water pressure (u_w) tends to pull the grains together.



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Representing Soil as a Continuous Medium

We will not be measuring soil properties on the micro (particle) level, as shown on Fig. 1.

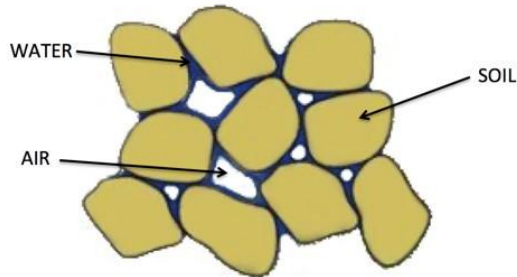


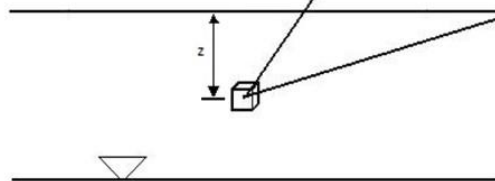
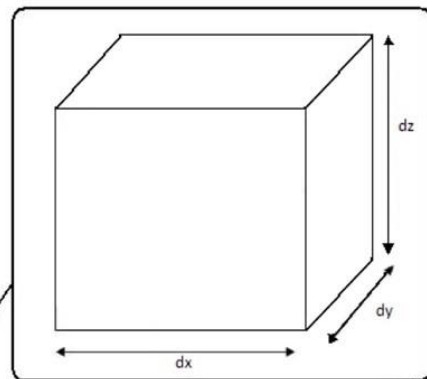
Fig 1: Soil at the micro level

However, it will be helpful from time to time to understand and discuss what is happening at the micro level.



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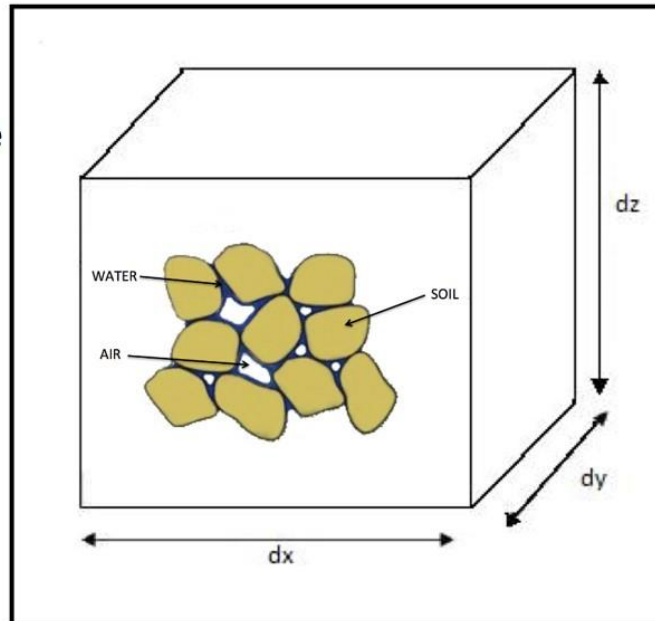
Consider a small element of soil, dx by dy by dz , located at a depth z below a horizontal ground surface as shown. This is often called a representative elemental volume (REV).



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The soil element is conceptually larger than the soil particle and void space size.

As shown, the cubical element contains a representative number of soil particles, air, and water.

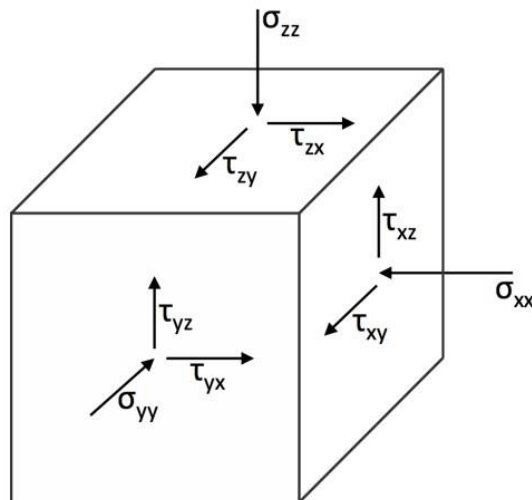


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Representing the Stresses on the REV

These stress values are often written as a **tensor**:

$$\begin{bmatrix} \sigma_{xx} & \tau_{xy} & \tau_{xz} \\ \tau_{yx} & \sigma_{yy} & \tau_{yz} \\ \tau_{zx} & \tau_{zy} & \sigma_{zz} \end{bmatrix}$$

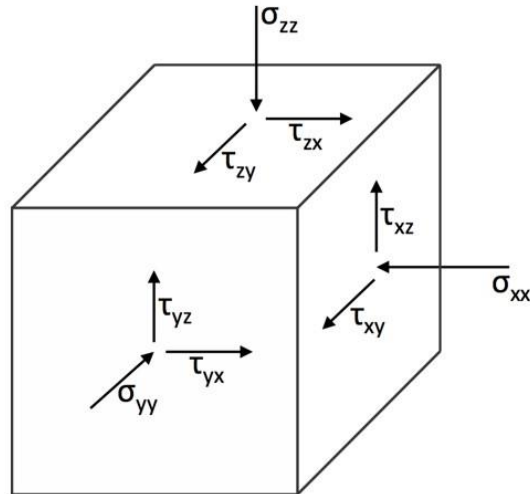


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Representing the Stresses on the REV

The stresses on the diagonal of the tensor are normal stresses, in that they act normal to the plane in question. The off-diagonal stresses are shear stresses and they act within the plane in question.

$$\begin{bmatrix} \sigma_{xx} & \tau_{xy} & \tau_{xz} \\ \tau_{yx} & \sigma_{yy} & \tau_{yz} \\ \tau_{zx} & \tau_{zy} & \sigma_{zz} \end{bmatrix}$$



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Representing the Stresses on the REV

- The normal stress σ_{xx} is sometimes shortened to σ_x , σ_{yy} to σ_y , etc.
- Fluid pressures that act within a soil mass such as pore air pressure (u_a) and pore water pressure (u_w) are incapable of sustaining any significant shear stresses and thus the tensors for these two stresses look like:

$$\begin{bmatrix} u_a & 0 & 0 \\ 0 & u_a & 0 \\ 0 & 0 & u_a \end{bmatrix} \quad \text{and} \quad \begin{bmatrix} u_w & 0 & 0 \\ 0 & u_w & 0 \\ 0 & 0 & u_w \end{bmatrix}$$



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Representing the Stresses on the REV

- Because the pore air and the pore water cannot sustain shear stresses, the magnitudes of these stresses is the same, regardless of the direction of action. Therefore, the diagonal terms are equal, as shown below.

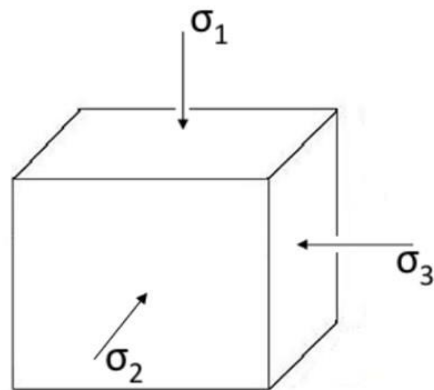
$$\begin{bmatrix} u_a & 0 & 0 \\ 0 & u_a & 0 \\ 0 & 0 & u_a \end{bmatrix} \quad \text{and} \quad \begin{bmatrix} u_w & 0 & 0 \\ 0 & u_w & 0 \\ 0 & 0 & u_w \end{bmatrix}$$



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Principal Planes and Stresses

- On three particular mutually perpendicular planes the shear stresses are found to be zero and these planes are called principal planes.

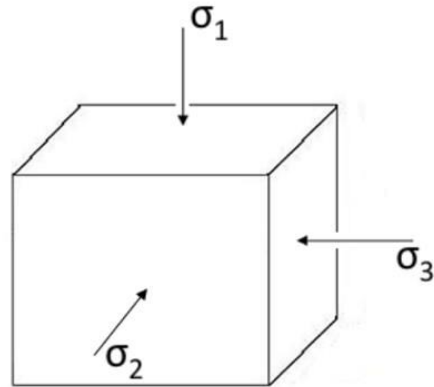


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Principal Planes and Stresses

- The normal stresses on these planes are called principal stresses and are designated:

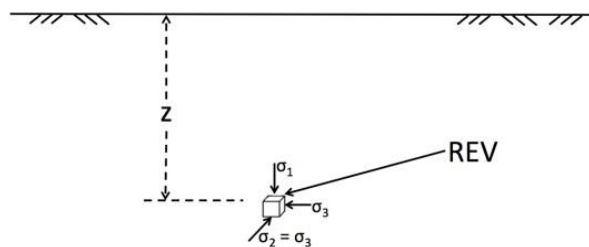
- σ_1 = major principal stress
- σ_2 = intermediate principal stress
- σ_3 = minor principal stress



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The Horizontal Ground Surface Case

- When the ground surface is horizontal and there are no structures applying load at or near the ground surface, the evaluation of principal stresses is relatively simple.



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The Horizontal Ground Surface Case

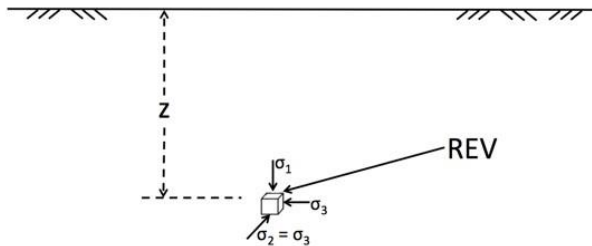
For this special case,

$$\sigma_1 = \sigma_{zz} = \sigma_z = \sigma_v$$

and $\sigma_2 = \sigma_3 = K\sigma_1$

where K = coefficient of lateral earth pressure for at rest conditions

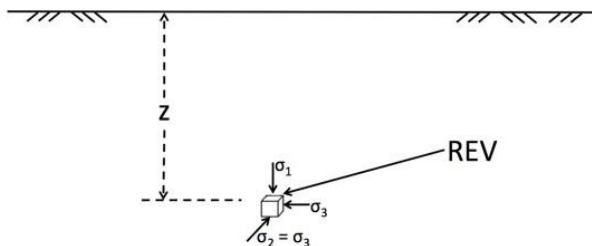
$$0.5 \leq K \leq 0.85$$



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The Horizontal Ground Surface Case

- Also, for this special case, the shear stresses are zero on all vertical planes, regardless of orientation.



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The Horizontal Ground Surface Case

Calculation of the Vertical Total Normal Stress

When the ground surface is horizontal, the total vertical normal stress (σ_v) is simply:

$$\sigma_v = \sigma_1 = \sigma_z = \sigma_{zz} = z * \gamma_m$$

where γ_m = total unit weight of the soil, which is also called the moist unit weight. It includes the weight of soil particles plus any water that is present.



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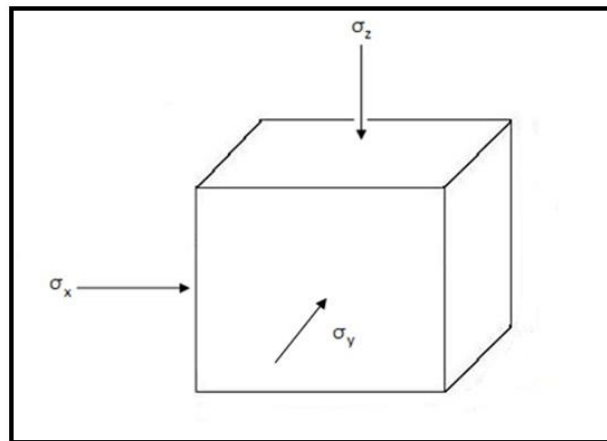
Calculating Total Stress

When the total normal stresses are principal stresses:

$$(\sigma_v = \sigma_1; \sigma_x = \sigma_y = \sigma_2 = \sigma_3)$$

- the state of total stress can be represented by a 9-element tensor with no off-diagonal terms that looks like:

$$\begin{bmatrix} \sigma_x & 0 & 0 \\ 0 & \sigma_y & 0 \\ 0 & 0 & \sigma_z \end{bmatrix}$$



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Stress State Variables

To review, there are three phases of an unsaturated soil that give rise to three stresses or pressures:

1. total stress = σ
2. pore air pressure = u_a
3. pore water pressure = u_w



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Stress State Variables

- **Total stress, σ** – the value of σ is always greater than zero and always greater than u_a . Thus $(\sigma - u_a)$, which is called net normal stress, is always positive.



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Stress State Variables

- **Pore air pressure, u_a** — when the degree of saturation is low and the air voids are interconnected, then u_a will typically be at equilibrium with the atmosphere above the ground surface. Because u_a is evaluated as a gage pressure (i.e. relative to atmospheric), it is typically zero or very near zero for these conditions.



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Stress State Variables

- **Pore water pressure, u_w** — The value of u_w can be negative, zero, or positive—but it is almost always negative when the soil is unsaturated.
- As a consequence, the **net fluid pressure ($u_a - u_w$)**— which is called **soil suction or matric suction**—is almost always positive in sign and corresponds to a net pressure that tends to pull the grains together.



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Stress State Variables

If we choose to combine these three stresses into two “net” stress state variables, we will have two variables that are measurable, both of which tend to keep the grains together when the soil is unsaturated:

1. The “net” normal stress ($\sigma - u_a$)
2. The matric suction ($u_a - u_w$)



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Stress State Variables

1. The “net” normal stress ($\sigma - u_a$)
2. The matric suction ($u_a - u_w$)

Research has shown that these **two stress state variables** control soil deformation and shear strength.



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Stress State Variables

- These stress state variables expressed in tensor form look like:

$$\begin{bmatrix} \sigma_1 - u_a & 0 & 0 \\ 0 & \sigma_2 - u_a & 0 \\ 0 & 0 & \sigma_3 - u_a \end{bmatrix} \text{ and } \begin{bmatrix} u_a - u_w & 0 & 0 \\ 0 & u_a - u_w & 0 \\ 0 & 0 & u_a - u_w \end{bmatrix}$$

principal net normal stresses soil suction



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Stress State Variables

The “**net**” normal stress ($\sigma - u_a$) pushes soil grains together; it is the difference between the total normal stress (σ) and the pore air pressure (u_a).

- All other things constant, when the net normal stress on the soil is increased, the soil becomes stiffer and stronger.



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Stress State Variables

The **matric suction** ($u_a - u_w$) acts to pull the grains together; it is the difference between the pore air pressure (u_a) and the pore water pressure (u_w).

- All other things constant, when the matric suction is increased (i.e. the water pressure becomes more negative), the soil becomes stiffer and stronger.



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Consider a Sand Castle

A simple example of how matric suction pulls grains together

- The net fluid pressure, matric suction ($u_a - u_w$), tends to pull the grains together.



Image via Wikipedia - http://en.wikipedia.org/wiki/File:Sand_sculpture.jpg



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Consider a Sand Castle

A simple example of how matric suction pulls grains together

- Thus, when building a sand castle, it is the matric suction (water in tension) that tends to pull grains of sand together, providing strength and stiffness.



Image via Wikipedia - http://en.wikipedia.org/wiki/File:Sand_sculpture.jpg



UNSATURATED SOILS

Consider a Sand Castle

A simple example of how matric suction pulls grains together

- When attempting to build a sand castle with sand that is completely dry (no water in the soil void space), it cannot be built because the sand particles will simply flow.



Image via Wikipedia - http://en.wikipedia.org/wiki/File:Sand_sculpture.jpg



UNSATURATED SOILS

Consider a Sand Castle

A simple example of how matric suction pulls grains together

- When some (but not too much) water is added to the sand, matric suction arises in the soil mass, and this soil suction provides strength and stiffness to the soil, “pulling” the grains together so that a sand castle can be constructed.

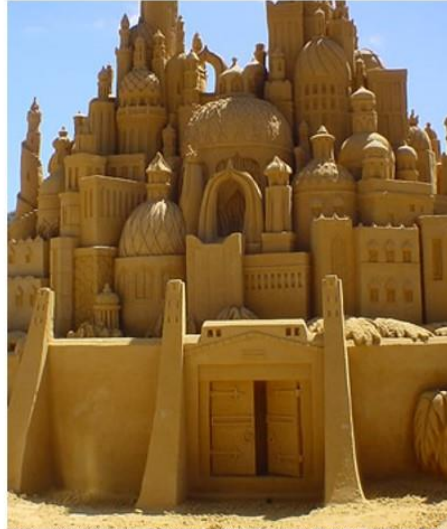


Image via Wikipedia - http://en.wikipedia.org/wiki/File:Sand_sculpture.jpg



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Consider a Sand Castle

A simple example of how matric suction pulls grains together

- In this way, the matric suction is effective in controlling the mechanical response of the soil.



Image via Wikipedia - http://en.wikipedia.org/wiki/File:Sand_sculpture.jpg



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Processes Leading to Changes in Soil Suction

The most common sources of soil suction change are:

- **wetting of the soil**
- **drying of the soil**



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Processes Leading to Changes in Soil Suction

Wetting of the soil – increasing the soil water content

- If soil is wetted, pore water pressure will become less negative.
- Soil particles will be less tightly pulled together.
- Some increase in volume of the soil might be expected.
 - This increase in volume for granular soils is typically quite small, but for many clay soils the increase is large and we call them **expansive soils**.
 - Also for more granular soils with initial very low density the effect of wetting may be densification and we call these **collapsible soils**.



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Processes Leading to Changes in Soil Suction

Drying of the soil – decreasing the soil water content

- If the soil is dried, pore water pressure becomes more negative.
- Soil grains are pulled together more tightly.
- Some decrease in volume of the soil mass may be expected.



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Consequences of a Change in Normal Stress

- When the total stress is changed (e.g. a building load is added) the net normal stress changes and some response of the soil is expected.
- This response is typically a compression of the underlying soil and a corresponding settlement of the building.



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Consequences of Changes in Stress State Variables

A soil response is expected, if:

1. the pore water pressure changes, causing a change in soil suction;
2. the total stress changes, causing a change in net normal stress; or
3. both stress state variables change simultaneously.



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Consequences of Changes in Stress State Variables

- A change in either stress state variable causes a response of the soil, such as compression or expansion, for example.
- If the net normal stress stays constant but the soil suction pressure changes (e.g. due to wetting of the soil) then a response of the soil is expected.



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Consequences of Changes in Stress State Variables

- On the other hand, if the soil suction remains constant (soil moisture content stays the same) but the net normal stress changes (e.g. the addition of a structural load), then a response of the soil is expected.



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Simplifications for Saturated Soil Conditions

- As an unsaturated soil becomes wetter, more of the void space is filled with water and less is filled with air.
- As water is added to an unsaturated soil and the soil becomes very wet, the pore air becomes discontinuous—it exists as bubbles.
- As the pore air becomes discontinuous and the air space in the voids approaches zero, the pore air pressure approaches the pore water pressure. This means that $(u_a - u_w)$ approaches zero.



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Simplifications for Saturated Soil Conditions

- As the air bubbles disappear, u_a disappears—at least its effectiveness disappears.
- Thus, for saturated soils, the remaining stresses are σ and u_w .



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Simplifications for Saturated Soil Conditions

Therefore, when the soil void space is filled with water, and the soil is saturated, the stress state is a function of two stresses:

1. Total Stress
2. Pore Water Pressure



UNSATURATED SOILS

Simplifications for Saturated Soil Conditions

Remember:

- Total stress tends to push the soil grains together
- **Negative pore water pressure** tends to pull the soil grains together

However, **when pore water pressure is positive**, the water pressure tends to push the soil grains apart.

- Pore water pressure is **negative** for saturated and unsaturated soils **above the groundwater table**.
- Pore water pressure is **positive** for saturated soils **below the groundwater table**.



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Simplifications for Saturated Soil Conditions

- For saturated soil conditions, it is possible to combine the total stress and pore water pressure into one “net” stress that is effective in controlling the deformation response and shear strength of saturated soils. This net stress is called the Effective Stress, σ' (Terzaghi, 1943)

Effective Stress

$$\sigma' = \sigma - u_w$$



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Simplifications for Saturated Soil Conditions

- The state of stress for a saturated soil can be represented by the following effective stress tensor:

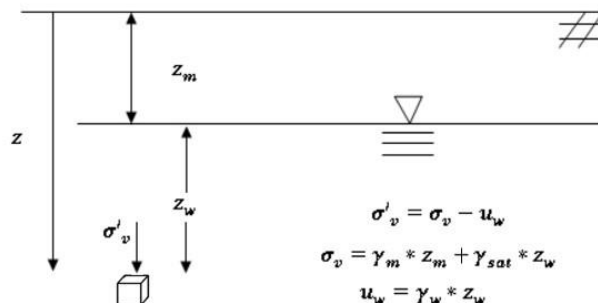
$$\begin{pmatrix} \sigma_x - u_w & \tau_{xy} & \tau_{xz} \\ \tau_{xy} & \sigma_y - u_w & \tau_{yz} \\ \tau_{xz} & \tau_{yz} & \sigma_z - u_w \end{pmatrix}$$



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Computation of Effective Stress

- The effective vertical stress for a small element of saturated soil located at depth z below a horizontal ground surface and depth z_w below the groundwater table is shown below.



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These are the opinions and work of the researchers and not of the National Science Foundation.



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APPENDIX B

SOIL-WATER CHARACTERISTIC CURVE LECTURE POWERPOINT

The Soil-Water Characteristic Curve

Arizona State University



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Surface Tension and Matric Suction

In an unsaturated soil, void space can be considered as analogous to a capillary tube such as that shown in **Figure 1.**

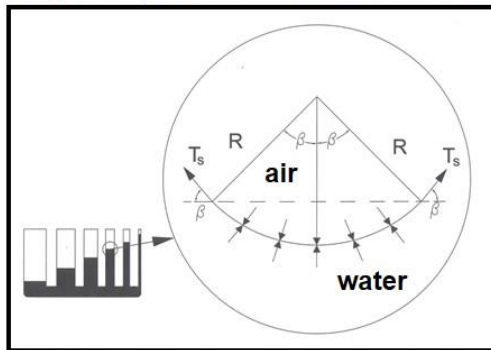


Fig 1 (Modified from Fredlund et al., 2011)



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Surface Tension and Matric Suction

The **air-water interface** is subjected to an air pressure, u_a , which is greater than the water pressure, u_w .

The pressure difference ($u_a - u_w$) is called **matric suction**.

This results in a surface tension, T_s , on the air-water interface.

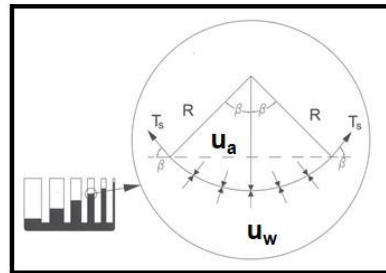


Fig 1



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Surface Tension and Matric Suction

$$(u_a - u_w) = \frac{2T_s}{R}$$

Where:

- ($u_a - u_w$) is the matric suction
- T_s is the surface tension
- R is the radius of curvature

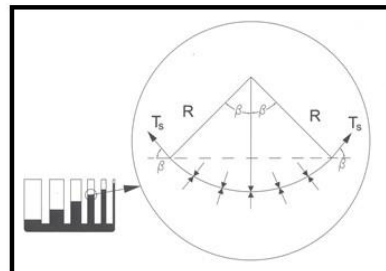


Fig 1



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Surface Tension and Matric Suction

As shown in **Figure 1**:

The smaller the capillary tube, the smaller the radius of curvature, and the higher the capillary rise.

By analogy, the smaller the pore size, the smaller the effective radius of curvature, and the higher matric suction that can be developed

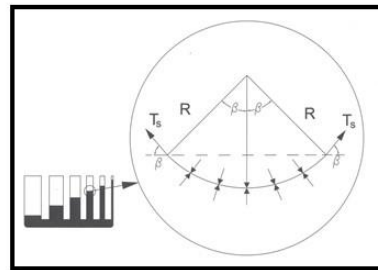


Fig 1



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Surface Tension and Matric Suction

For example:

Clays have smaller pores, and therefore sustain matric suction greater than sands at the same water content.

As the soil dries, the water recedes into the pores and the radius of curvature decreases. As R_s decreases, the soil matric suction increases.

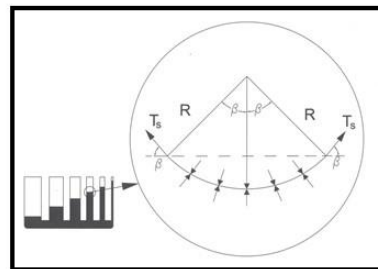


Fig 1



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Surface Tension and Matric Suction

That means:

Fine-grained soils require higher air pressure for air to enter the pores, than coarse-grained materials.

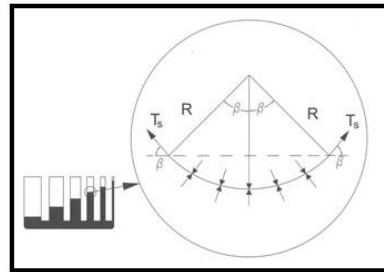


Fig 1



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Soil-Water Characteristic Curve (SWCC)

For a given unsaturated soil, the amount of water relative to the amount of air in the soil pore space is related to the radius of curvature of the water.

The lower the water content, the smaller the radius of curvature, and the higher the soil matric suction.

The drier the soil, the greater the matric suction



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Soil-Water Characteristic Curve (SWCC)

Note on the TWO STRESS STATE VARIABLES:

It is important to note that the **matric suction** is one of the two stress state variables controlling unsaturated soil shear strength and volume change response.

The other stress variable is the **net normal stress**, which is the difference between the total external stress applied to the soil minus the pore air pressure ($\sigma - u_a$).



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Soil-Water Characteristic Curve (SWCC)

As the soil is composed of a range of pore sizes, the pores will drain at different capillary pressures.

The relationship between some measure of water content and the matric suction of a soil is called the **soil-water characteristic curve** (SWCC).



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Soil-Water Characteristic Curve (SWCC)

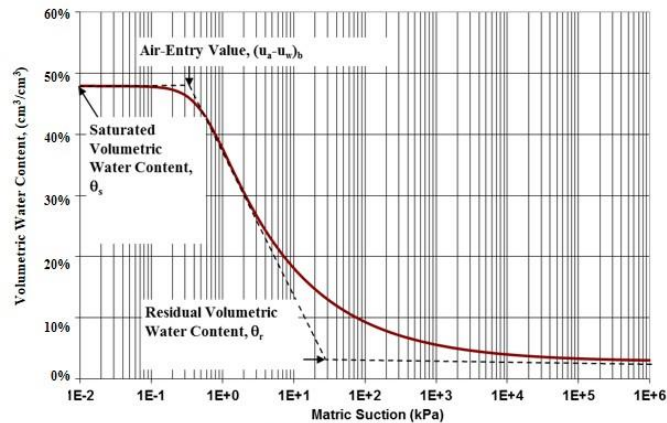


Figure 2



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Soil-Water Characteristic Curve (SWCC)

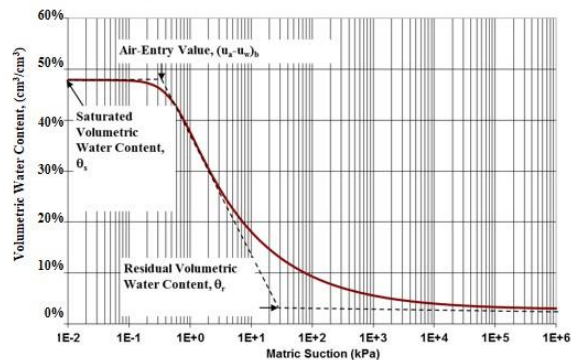
In **Figure 2**: The measure of soil water content shown is the volumetric water content (θ_w), which is defined as:

$$\theta_w = (V_w / V_t) \times 100\%$$

Where:

V_w = volume of water

V_t = total volume of the soil



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Soil-Water Characteristic Curve (SWCC)

The SWCC can also be defined in terms of:

- Degree of saturation
- Gravimetric water content.

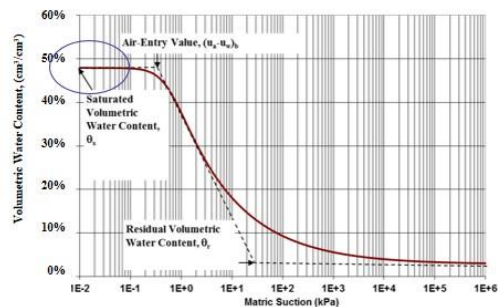


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Soil-Water Characteristic Curve (SWCC)

The water content related parameters used to describe the SWCC include:

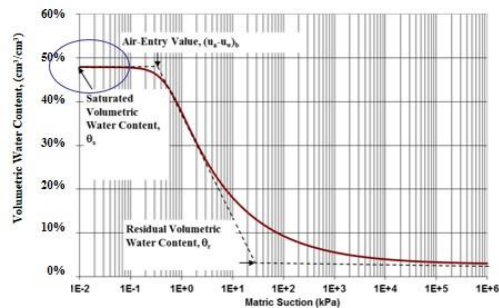
The saturated volumetric water content, θ_s , which is the water content that is achieved when the saturation condition is established.



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Soil-Water Characteristic Curve (SWCC)

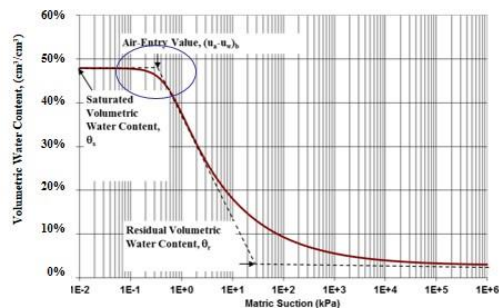
The θ_s is the same as the **porosity** of the soil when the pores are completely filled with water.



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Soil-Water Characteristic Curve (SWCC)

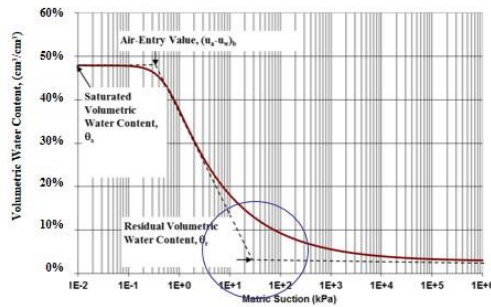
The **air-entry value** is the matric suction value that must be exceeded before air recedes into the soil pores.



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Soil-Water Characteristic Curve (SWCC)

The **residual volumetric water content** is the volumetric water content from which a change in water content with respect to a change in suction becomes zero.

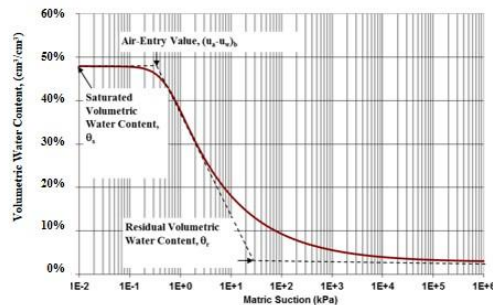


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Soil-Water Characteristic Curve (SWCC)

The SWCC relationship is non-linear and takes on a more or less **sigmoidal** curve shape.

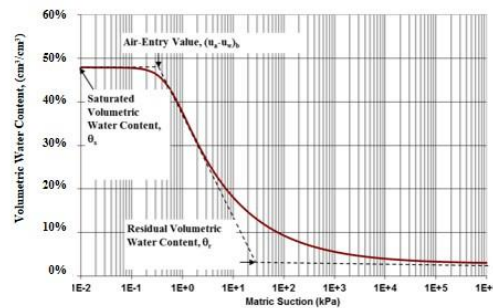
As a soil becomes wetted, the pore-water pressure (u_w) becomes less negative.



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Soil-Water Characteristic Curve (SWCC)

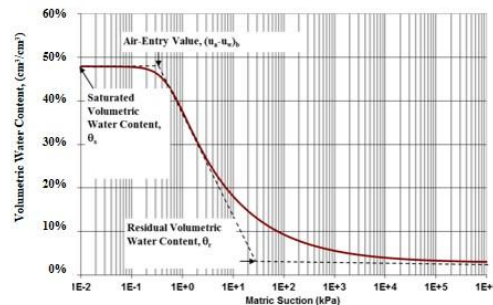
As the **degree of saturation of the soil approaches 100%**, u_w approaches the pore-air pressure (u_a), and the matric suction approaches zero.



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Soil-Water Characteristic Curve (SWCC)

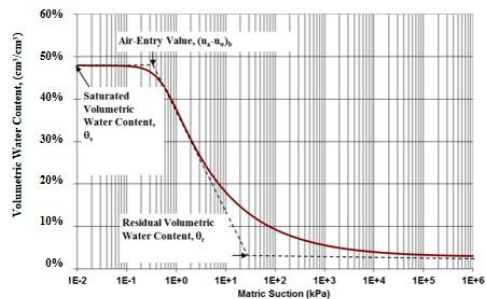
Conversely, when the soil is **very dry**, the matric suction can become quite high, and approaches a value of about 1×10^6 kPa for a completely dry state (Fredlund et al., 2011).



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Soil-Water Characteristic Curve (SWCC)

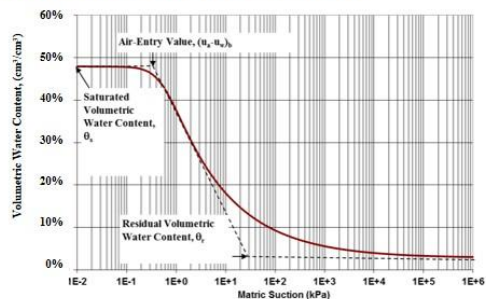
When we plot the SWCC, the matric suction is plotted on a **log scale** and the water content measure is plotted **arithmetically**.



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Soil-Water Characteristic Curve (SWCC)

The matric suction is plotted on a log scale because there is a **very wide range of matric suction values** associated with moisture conditions of interest in geotechnical engineering.



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Comparing SWCC for Different Soil Types

The shape of SWCC is dependent on the **type of soil**. Typical SWCCs for clay, silt and sand are presented in **Figure 3**.

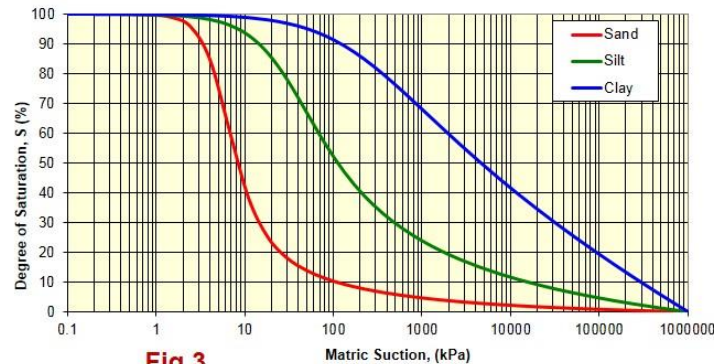


Fig 3



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Comparing SWCC for Different Soil Types

The **amount of fines** and the **plasticity index** of the soil influence the SWCC.

Notice that **at the same suction level**, plastic soils retain more water than non-cohesive or granular materials.

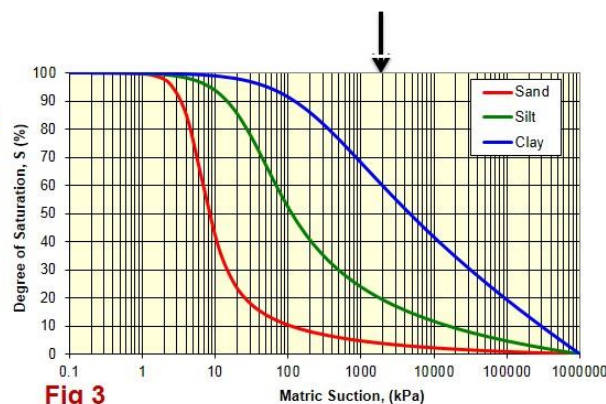


Fig 3



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Mathematical Representation of the SWCC

The development of a SWCC for a particular soil can be done through laboratory testing, requiring several points on the SWCC to be measured.

In addition, several **mathematical models have been developed to describe the SWCC** for a particular soil from just a few measured points.



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Mathematical Representation of the SWCC

The process of fitting experimental suction data to one of the proposed equations requires a **minimum number of experimentally obtained suction measurements**, depending upon the number of unknown parameters in the chosen function.



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Mathematical Representation of the SWCC

One of the most commonly used equations is that presented by **Fredlund and Xing (1994)**, in terms of volumetric water content (θ_w):

$$\theta_w = C(\psi) \times \left[\frac{\theta_s}{\left[\ln \left[\exp(1) + \left(\frac{\psi}{a} \right)^b \right] \right]^c} \right]$$

Where:

ψ is the **matric suction** = $(u_a - u_w)$



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Mathematical Representation of the SWCC

a is a parameter related to the air entry value of the soil (kPa)

b is a soil parameter related to the desaturation rate, after the air entry value has been exceeded

c is a parameter related to the residual water content

θ_s is the saturated volumetric water content.

$$\theta_w = C(\psi) \times \left[\frac{\theta_s}{\left[\ln \left[\exp(1) + \left(\frac{\psi}{a} \right)^b \right] \right]^c} \right]$$



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Mathematical Representation of the SWCC

The $C(\psi)$ term is a **correction factor** to **force the suction to one million kPa** when the volumetric water content is equal to zero:

$$C(\psi) = \left[1 - \frac{\ln\left(1 + \frac{\psi}{h_r}\right)}{\ln\left(1 + \frac{10^6}{h_r}\right)} \right]$$

Where: h_r is a fitting parameter.

$$\theta_w = C(\psi) \times \left[\frac{\theta_s}{\ln\left[\exp(1) + \left(\frac{\psi}{a}\right)^b\right]^c} \right]$$



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Soil-Water Characteristic Curve Prediction

- When measured soil suction data is not available, the SWCC can be roughly **estimated** from grain-size distribution parameters and other soil properties.
- Often these relationships are based on **correlations with commonly obtained soil index parameters**, including **Atterberg limits** and **grain-size distribution**.
- In some cases, SWCCs are estimated using a **large database** of SWCC's by matching key soil characteristics.



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Example

Zapata (1999) proposed the following equations **to predict the fitting parameters for the Fredlund and Xing** equation for plastic soils (Zapata et al. 2000):

$$a = 0.00364(wPI)^{3.35} + 4(wPI) + 11$$

$$\frac{b}{c} = -2.313(wPI)^{0.14} + 5$$

$$c = 0.0514(wPI)^{0.465} + 0.5$$

$$\frac{h_r}{a} = 32.44e^{0.0186(wPI)}$$



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Example

The **wPI** parameter is defined as:

$$wPI = \% \text{ Passing } \#200 \times PI / 100$$

Where:

- **% Passing #200** is the percentage passing the #200 U.S. standard sieve, and
- **PI** is the Plasticity Index.



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Example

Once the parameters are replaced in the Fredlund and Xing equation, the family of SWCC curves presented in **Figure 4** can be obtained.

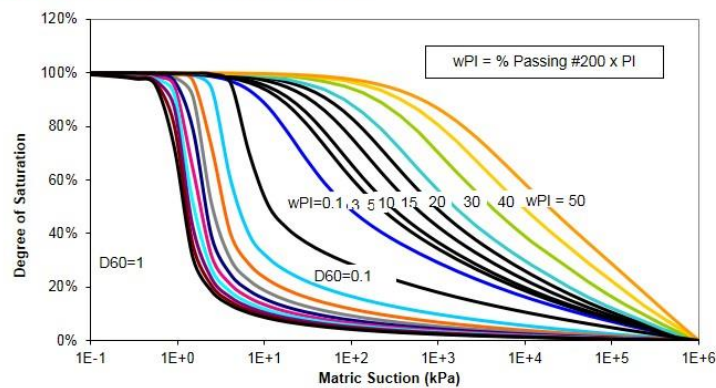


Figure 4 (Zapata et al., 2000)



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Common Uses of the SWCC in Geotechnical Engineering



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Estimation of Shear Strength for Unsaturated Soils

Vanapalli et al. (1996): general equation

$$\tau = c' + (\sigma - u_a)\tan\phi' + (u_a - u_w)\left(\frac{\theta_w - \theta_r}{\theta_s - \theta_r}\right)(\tan\phi')$$

θ_w : volumetric water content
 θ_r : volumetric water content at residual suction
 θ_s : volumetric water content at saturation

Prediction using the SWCC

Fredlund et al. (1995): κ equation

$$\tau = c' + (\sigma - u_a)\tan\phi' + (u_a - u_w)(\theta^K)(\tan\phi')$$

θ : normalized volumetric water content defined by θ_w/θ_s , which is also equal to degree of saturation

Prediction using the SWCC and fitting parameter κ



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Estimation of Hydraulic Conductivity of Unsaturated Soils

$$k_w = k_s \frac{[1 - \alpha\psi^{n-1}(1 + \alpha\psi^n)^{-m}]^2}{[1 + \alpha\psi^n]^{\frac{m}{2}}}$$

van Genuchten and Mualem (van Genuchten 1980)

Where: - k_w is the hydraulic conductivity of an unsaturated soil
 - k_s is the saturated hydraulic conductivity
 - ψ is the soil matric suction, and
 - m , n and α are fitting parameters.



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Methods Available to Measure Matric Suction

Matric suction can be measured **directly** or **indirectly**.

Direct methods are used to measure the negative pore water pressure.

If the pore air pressure is kept atmospheric, then the matric suction (ψ) is equal to:

$$\psi = u_a - u_w = 0 - u_w = -u_w$$



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Methods Available to Measure Matric Suction

Direct methods:

- Oedometer Pressure Plate Device
- Tempe Pressure Cells
- Tensiometers



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Methods Available to Measure Matric Suction

The **axis-translation technique** is a common method used for the direct measurement of soil matric suction.

Detailed information about the axis-translation principles are given in the laboratory module (next).



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These are the opinions and work of the researchers and not of the National Science Foundation.



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APPENDIX C

AXIS-TRANSLATION LECTURE POWERPOINT PRESENTATION

Axis-Translation

Pre-lab Lecture



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Axis-Translation

Topics Covered

- Soil Suction
- Measuring Matric Suction
- Axis-Translation in the Lab



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Soil Suction

Two Primary Components

- Matric Suction
- Osmotic Suction

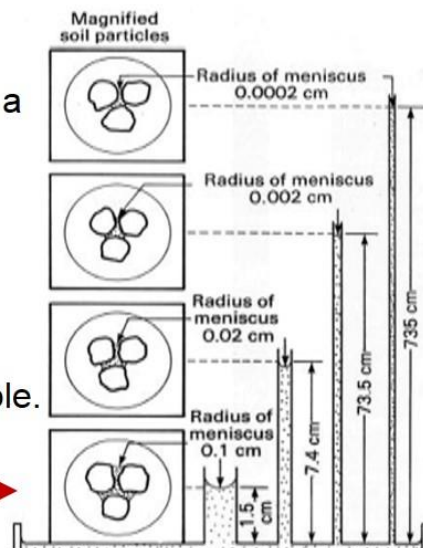


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Matric Suction

Matric suction is commonly associated with **capillary phenomenon**, the rise of water in a tube due to the surface tension of the water.

- Pores in soil are similar to capillary tubes with small radii.
- The soil creates capillaries that raise soil-water above water table.
- Smaller particle sizes = higher capillary rise.



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Matric Suction

- Capillary water has negative pressure with respect to air pressure, which is generally atmospheric ($u_a = 0$).
 - This means that the water is in tension for unsaturated conditions
- Pore-water pressure can be highly negative when saturation is low.

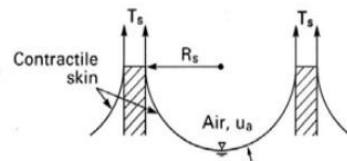


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Matric Suction

Consider the water in one of those capillaries:

- The water level at the top of the tube "curves." This curvature is called a **meniscus**.
- The radius of the meniscus is inversely proportional to matric suction ($u_a - u_w$).
- The higher the radius of curvature, the lower the matric suction.



The University of Virginia
Physics Department

$$(u_a - u_w)_d = \frac{2T_s}{R_s}$$

Kelvin Equation



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Measuring Matric Suction

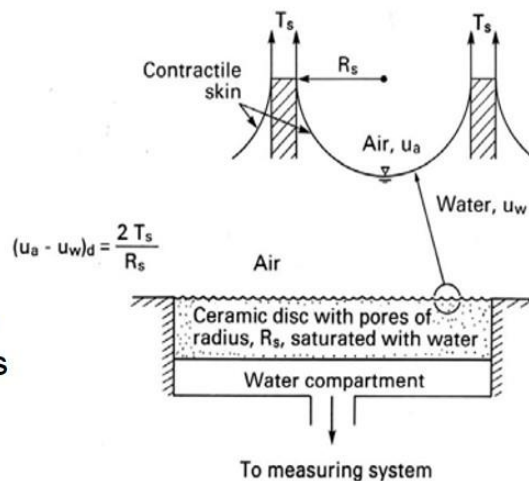
- One way to measure matric suction is to directly measure or control $-u_w$ and u_a .
- Because u_w is commonly highly negative, measuring or controlling u_w in the lab often requires increasing u_a to avoid cavitation of water in the measurement device.



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Measuring Matric Suction

- **High air-entry ceramic disks**, which are uniformly porous and separate air and water, are used.
- If the disk is saturated with water, air cannot pass through it since the air-water interface resists the flow of free air.



Modified from Fredlund and Rahardjo, 1993



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Measuring Matric Suction

- The **surface tension** (T_s) of the water in the disk dictates its ability to withstand the flow of free air.
- The air-water interface joins the small pores of **radius** (R_s) on the ceramic disk's surface.
- The difference between the air pressure above the interface and the water pressure below is the **matric suction**. (Hence: $u_a - u_w$)
- The maximum matric suction that can be maintained across the surface of the disk is called its **air-entry value**, or $(u_a - u_w)_d$.



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Measuring Matric Suction

- A high air-entry disk can only separate the air and water pressures if the soil's matric suction is not greater than the disk's air-entry value.
- If the matric suction exceeds the air-entry value, air will freely pass through the disk and enter the measuring system.
- This air in the measuring system forces water back through the disk and into the soil sample.
- This causes an **erroneous measurement** of the soil's pore-water pressure.



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Air-Entry Value

- Table 4.3 shows examples of various disks and pore sizes (Soil-moisture Corporation).

Table 4.3 Properties of High Air-Entry Disks Manufactured by Soilmoisture Equipment Corporation¹ (Manufacturer's Results)

Type of Disks	Approximate Pore Diameter ($\times 10^{-3} \text{ mm}$)	Measured Air-Entry Value, $(u_a - u_w)_d, \text{ kPa}$
½ bar High flow	6.0	48-62
1 bar	2.1	138-207
1 bar High flow	2.5	131-193
2 bar	1.2	241-310
3 bar	0.8	317-483
5 bar	0.5	> 550
15 bar	0.16	> 1520

¹ Soilmoisture Equipment Corporation, Santa Barbara, CA, USA

NOTE: The disks are identified by a specified air-entry values expressed in bars, (i.e., one bar is equal to 100 kPa).



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Axis-Translation in the Lab

- We can directly measure matric suction in the lab using the axis-translation technique.
- This technique can be used for both compacted and undisturbed soil samples.



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Axis-Translation in the Lab: Procedure

- Place a soil sample on top of a saturated high air-entry disk in an air pressure chamber. (Air-entry must be higher than matric suction).
- Place a weight on the sample to make sure the soil and disk are in contact.

Note: The above steps should be done as quickly as possible, to preserve the specimen matric suction by minimizing drying of the specimen.

- Assemble the SWCC or Tempe Cell



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Axis-Translation in the Lab: Procedure

- Keep water pressure as close to zero as possible in the compartment below the air-entry disc by increasing chamber air pressure to prevent water movement in to or out of the specimen.
- Flush air bubbles out of the lower compartment in order to keep upper compartment saturated with water and to avoid erroneous readings in the volume device.
 - This keeps upper compartment saturated with water



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Axis-Translation in the Lab

- Highly negative pore-water pressures can be measured with a pressure cell apparatus. →
- Use the air pressure chamber and water pressure at equilibrium to determine matric suction ($u_a - u_w$).

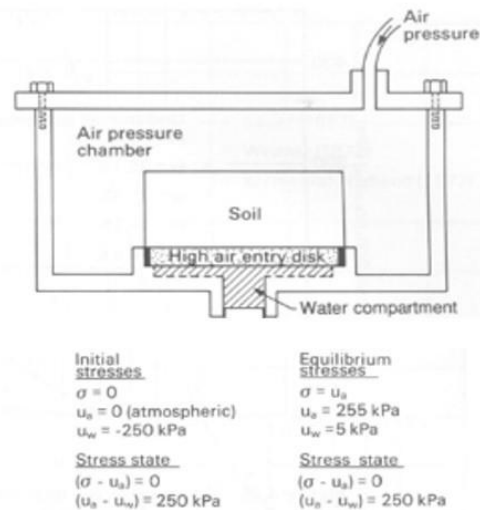


Fig. 4.27



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Axis-Translation in the Lab

- This procedure changes the atmospheric pressure in the chamber to move the origin of reference for the pore-water pressure from the standard level to the final air pressure in the chamber.
- This is why the procedure is called "axis-translation."
- Cavitation is prevented** because water pressure in the measuring system **does not** become highly negative.



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Axis-Translation in the Lab

Example:

- Let's suppose the soil specimen initially has a matric suction $(u_a - u_w) = 250 \text{ kPa}$ when placed on a saturated high air-entry disk
- The specimen will immediately tend to draw water up through the ceramic disk.
- Increasing the chamber's air pressure tends to mitigate upward water flow through the air-entry disk.

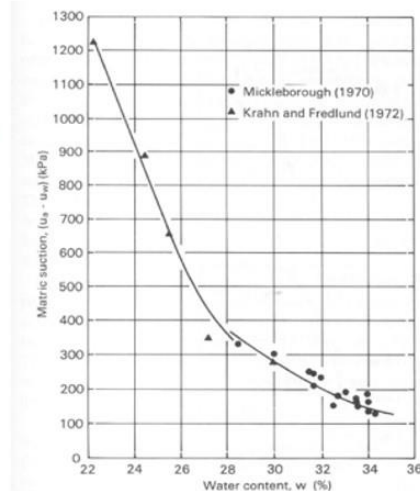


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Axis-Translation in the Lab

Determining the SWCC with the Axis-Translation method

- The SWCC shows that as water content increases, matric suction decreases (see Figure).
- The Mickleborough and Krahn & Fredlund points on the curve represent the various measurements at different air pressure levels.



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Axis-Translation Method to Obtain the SWCC

- The SWCC is normally determined by controlling the matric suction to a specified series of values.
- For a given specified matric suction value of interest (e.g. 100 kPa), the pore-water pressure is held at zero while the air pressure is increased to the matric suction value of interest (e.g. 100 kPa).
- Water will tend to be pulled into or pushed out of the sample to achieve equilibrium with the **set** matric suction value.



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Axis-Translation Method to Obtain the SWCC

- Once there is no longer a tendency for water to move in or out of the specimen, equilibrium has been reached.
- By observing the amount of water that have come into or out of the specimen, an adjustment to the specimen initial water content can be made to obtain the water content consistent with the matric suction of interest (e.g. 100kPa).
- Now, the matric suction can be changed to another value of interest by increasing (or decreasing) the air pressure while holding pore water pressure to zero.



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Laboratory Manuals

- Manuals are available to determine the SWCC in the laboratory
 - SWC-150 device
 - Tempe Cell device



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APPENDIX D

TEMPE PRESSURE CELL LABORATORY MANUAL

Tempe Cell Test

Introduction

The soil-water characteristic curve defines the amount of water in a soil versus soil suction. The soil-water characteristic curve has emerged as a practical and sufficiently accurate tool for the estimation of unsaturated soil property functions for most geotechnical engineering problems. The soil-water characteristic curve (SWCC) has an important role in the implementation of unsaturated soil mechanics. The SWCC was initially viewed as a means of estimating in situ-soil suction by measuring the natural water content and using the SWCC as a fixed relationship between suction and water content to estimate suction. As an example of characterizing unsaturated soils; when these soils are wetted they could potentially expand or collapse. These conditions can be problematic, causing structural damage which is costly to fix. This is why it is essential to run tests on these soils to understand what will happen to the soil once it is wet or saturated with water or any other fluid. The Tempe cell test is used to determine the SWCC. Thus, the SWCC has become viewed as the key to the implementation of unsaturated soil mechanics in engineering practice. The SWCC has proven to be an interpretive model that uses the elementary capillary model to provide an understanding of the distribution of water in the air voids. The effects of soil texture, gradation, and void ratio all have become part of the interpretation of measured laboratory soil-water characteristic curve data.

The amount of water in the soil can be defined as follows:

$$w = \frac{m_w}{m_d} * 100\%$$

Where,

w = water content

m_w = mass of moist soil

m_d = mass of dry soil

The SWCC can be constructed by knowing the matric suction of the soil at particular water content.

The purpose of this test is to construct the soil-water characteristic curve (SWCC) for a particular soil. Determination of the SWCC is not easy and very time consuming. It shows the relationship between the matric suction (water suction) and gravimetric water content of a soil. Matric suction is defined as the difference between the air pressure and the water pressure ($u_a - u_w$) in the pores of the material. By using the axis-translation

technique (explained elsewhere), we maintain the u_w essentially equal to zero while we can apply u_a to the soil. In this case, the suction is equal to the u_a . As the matric suction increases, the water content will decrease due to water suction in the unsaturated soil. In this lab, you will apply various air pressures to the soil specimen in order to find the water content at equilibrium at each pressure and then construct the soil-water characteristic curve.

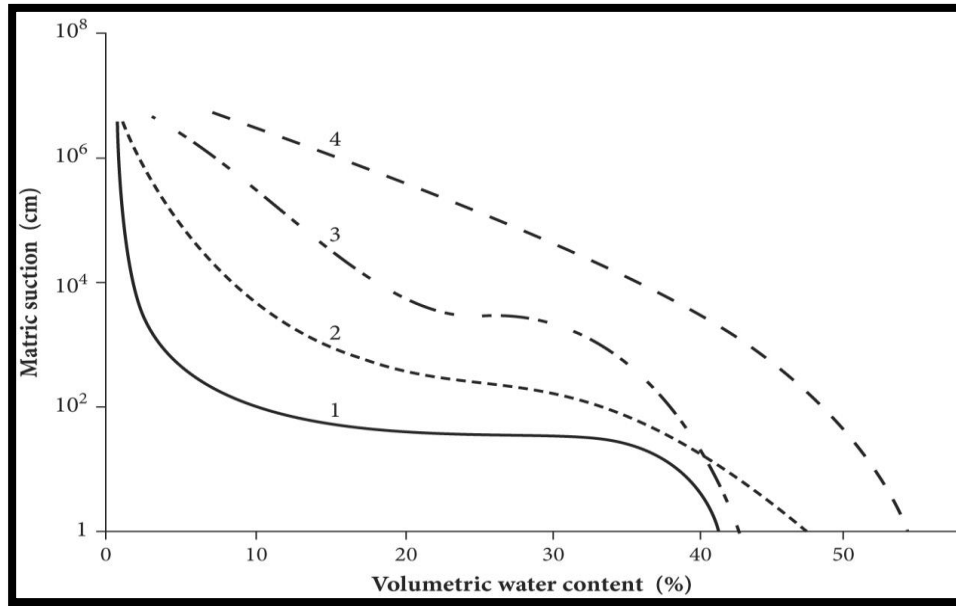


Figure 1: Examples of Soil-Water Characteristic Curves

Apparatus and Supplies

Tempe Cell Equipment (See Figure2)

1. Brass Cylinder
2. Top Cap Assembly
3. Base Cap
4. 2 "O" Rings Seal
5. Porous Ceramic Plate (1 Bar Plate)
6. Tempe Stud Assembly

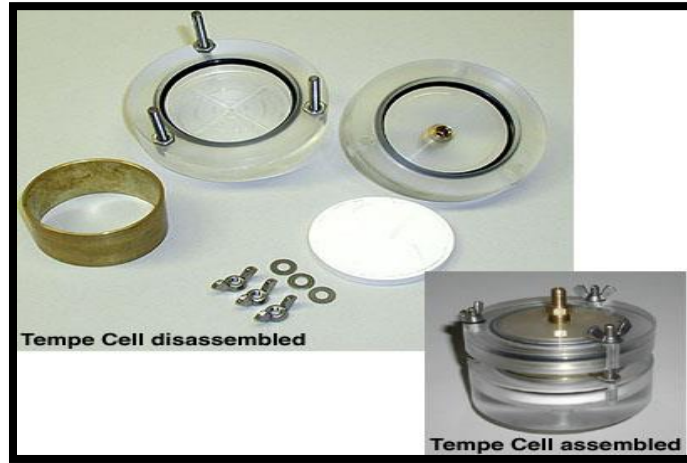


Figure 2: Tempe Cell Equipment

Other Equipment Needed

1. 2 Porous Stones
2. Sharp-edge knife
3. Balance
4. Drying oven
5. Spatula
6. 2 plastic sandwich bags
7. Filter paper
8. Air compressor for compressed air
9. Air pressure inlet tube
10. Containers-handling samples (tin or aluminum moisture cans)
11. Gloves for moving and handling hot containers after drying
12. Scoop
13. Container to saturate sample
14. Water

Samples

1. Soil samples shall be preserved and transported in accordance with ASTM Test Method D 4220 Groups B, C, or D Soils. Keep the samples that are stored prior to testing in non-corrodible airtight containers at a temperature between approximately 3°C and 30°C and in an area that prevents direct contact with sunlight. Disturbed samples in jars or other containers shall be stored in such a way as to reduce moisture condensation on the insides of the containers.
2. The water contents determination should be done as soon as practical after sampling, especially if potentially corrodible containers (such as thin-walled steel tubes, paint cans, etc.) or plastic sample bags are used.

Soil Type Recommendation

Using a certain soil for students to use is crucial in conducting a proper laboratory test for unsaturated soils. The following table shows the characteristics of the soil recommended for the students to use. These soil properties were determined for reasonable equilibrium times and ease of use.

Table 1: Optimum Soil Properties for Use by Students

Soil Type	Gradation Type	Specific Gravity	Liquid Limit (LL)	Plastic Index (PI)
Silt	Well Graded	2.73	20-28	3-7

Soil Index Property Determinations

The determination of some index properties is an important step prior to the Tempe Cell Test. It will be needed during the analysis section of the report. The following properties should be determined prior to this test:

1. *Specific Gravity of Solids*- The specific gravity shall be determined in accordance with ASTM Test Method D 854 on the soil being used.
2. *Atterberg Limits*- The liquid limit, plastic limit, and plasticity index shall be determined in accordance with ASTM Test Method D 4318 of the soil being used. Atterberg limits are necessary for proper soil classification but are not required for this test method.
3. *Particle Size Distribution*- The particle size distribution shall be determined in accordance with ASTM Test Method D 422 on the soil being used. Particle size distribution is not required for this test but it is necessary to help with visual inspection of the soil specially if it substantial fraction of coarse-grained material is present.
4. *Standard Modified Proctor Test*- The standard proctor test shall be determined in accordance with ASTM Test Method D 698. Determining the maximum dry unit weight and optimum moisture content is needed for the analysis section of the report.

Procedure

Reminder: Always wear goggles and lab coats.

Part I: Initial water content determination and sample saturation

1. Saturate one-bar ceramic porous plate with deaerated water for a minimum of 24 hours with a stainless steel or plastic container.
2. Homogenize the soil to be tested.
3. Gather a small soil sample for water content determination.
4. Weigh and record mass of tin can.
5. Add a small sample of the soil into the tin can. Measure and record the mass of the tin can + soil.
6. Place tin can + soil in the oven at 110°C for a minimum of 24 hours.

7. After soil has been in the oven for 24 hours, measure and record the mass of the tin can + soil.
8. Calculate the initial water content of the soil.
9. Measure and record the height and diameter of a brass cylinder. Use 3 measurements and calculate the average.
10. Measure and record the mass of the porous stone, filter paper, and brass cylinder.
11. Place filter paper on top of the porous stone.
12. Place the brass cylinder on top of the filter paper.
13. Fill the cylinder to approximately 1/2 of its height and compact the soil with a compaction hammer 10 to 15 times depending upon composition of the soil. Repeat two more times until the brass cylinder is completely full of compacted soil.
14. Once soil is compacted into the brass cylinder remove excess soil from the top of the cylinder with a spatula and make sure it is leveled out.
15. Measure and record the mass of the porous plate, filter paper, brass cylinder, and compacted soil.
16. Place another filter paper on top of the brass cylinder filled with the soil.
17. Place another porous plate on top of the newly placed filter paper.
18. Take the whole sample and place in a deep pan to where the water level is at around $\frac{2}{3}$ the height of the brass ring.
19. Allow soil to soak the water until saturation is achieved. For sandy soil, it will take approximately 30 to 60 minutes.

Part II: Tempe cell assemblage

20. After the sample has been saturated, remove all the assemblage from the pan.
21. Place the saturated one-bar ceramic stone in the Tempe cell.
22. Cut a new filter paper to the circumference of the brass cylinder and place on the one-bar stone. Add a clean "O" ring gasket to the base cap assembly. Remove both used filters from brass cylinder.
23. Place brass cylinder with compacted saturated soil in base cap assembly on top of the filter paper.
24. Add top cap assembly and hand-tighten fly nuts.
25. Place a beaker under the Tempe cell assembly to catch water draining from the saturated soil.
26. Adjust the gauge to a known desired pressure.
27. Allow the water from the soil to drain from Tempe cell until the soil reaches equilibrium and doesn't release anymore water. The equilibrium time varies as a function of the soil type. For sand, it typically takes 1 to 2 days, while silty material will need from 3 to 4 days.

Part III: Tempe cell disassemble and final water content determination

28. Weigh and record tin can the soil sample will be placed in to for water content determination.

29. Turn pressure gauge off and remove top cap of the Tempe cell.
30. Take a sample from the middle of the soil and place it in the tin.
31. Measure and record mass of the tin + soil sample.
32. Place in oven for at least 24 hrs.
33. Remove from oven and record its mass.
34. Calculate and record the water content of the sample.
35. If you are limited to using only one Tempe cell at a time repeat steps for each desired pressure level.
36. Once you have recorded the water content at various pressures, plot these points in order to construct the SWCC.

Data

Specimen Data

At beginning of test:

- 1) Height of brass cylinder (mm)
- 2) Diameter of brass cylinder (mm)
- 3) Mass of porous stone plate (g)
- 4) Mass of filter paper (g)
- 5) Brass cylinder (g)
- 6) Plate+ filter paper+ brass cylinder + soil (g)
- 7) Soil (g)
- 8) Mass of tin can (g)

Initial water content:

- 1) Mass of tin can (g)
- 2) Mass of moist specimen plus can (g)
- 3) Mass of moist specimen
- 4) Mass of entire dry specimen plus can (g)
- 5) Mass of dry specimen plus can (g)
- 6) Mass of dry specimen

For water content determination:

- 1) Mass of tin can (g)
- 2) Mass of moist specimen plus can (g)
- 3) Mass of moist specimen
- 4) Mass of entire dry specimen plus can (g)
- 5) Mass of dry specimen plus can (g)
- 6) Mass of dry specimen

Soils Testing Laboratory **Tempe Cell Test**

Sample No.: _____

Location: _____

Tested By: _____

Type of Soil: _____

Date of Test: _____

At Beginning of Test:

Brass cylinder measurements

	1	2	3	Average (mm)
At _____ kPa Height (H)				
At _____ kPa Height (H)				
At _____ kPa Height (H)				
At _____ kPa Diameter (D)				
At _____ kPa Diameter (D)				
At _____ kPa Diameter (D)				

Volume of brass cylinder

At ____ kPa Volume (mm^3)	At ____ kPa Volume (mm^3)	At ____ kPa Volume (mm^3)

Volume Equation:

$$V = \frac{H * \pi * D^2}{4}$$

Initial water content determination:

Soil before soil is dried in the oven

	Initial Mass (g)
Tin Can	
Tin + Soil,	
Soil, m_w	

Soil after soil is dried in the oven

	Initial Mass (g)
Tin + Soil,	
Soil, m_w	

Initial water content of soil

Initial Water Content (%)

Water Content Equation:

$$w = \frac{m_{\text{water}}}{m_{\text{solids}}} * 100\% = \frac{m_w - m_d}{m_d} * 100\%$$

Where

m_w = mass of wet soil

m_d = mass of dry soil

Amount of soil needed for specimen:

Amount of soil needed for specimen

	At ____ kPa	At ____ kPa	At ____ kPa
Initial water content, w_{initial} (%)			
Optimum water content, w_{opt} (%)			
95% of maximum dry unit weight, $\gamma_{95\% \text{ dry max}}$ (kN/m^3)			
95% of maximum moist unit weight, $\gamma_{95\% \text{ moist max}}$ (kN/m^3)			
Volume of specimen brass ring, V (m^3)			
Moist mass needed for specimen, m (g)			

Maximum moist unit weight calculation:

$$\gamma_{95\% \text{ moist max}} = \gamma_{95\% \text{ dry max}} * (1 + w_{opt})$$

Moist mass needed calculation:

$$m = \frac{\gamma_{95\% \text{ moist max}} * V}{g}$$

Where

$\gamma_{95\% \text{ dry max}}$ = 95% of maximum dry unit weight
 $\gamma_{95\% \text{ moist max}}$ = 95% of maximum moist unit weight
 w_{opt} = optimum water content (as a decimal)
 m = mass of soil inside cylinder
 V = volume of brass cylinder
 g = gravity

At End of Test:

Soil before soil is dried in the oven

	At ____ kPa Mass (g)	At ____ kPa Mass (g)	At ____ kPa Mass (g)
Tin Can			
Tin + Soil,			
Soil, m_w			

After soil is dried in oven

	At ____ kPa Mass (g)	At ____ kPa Mass (g)	At ____ kPa Mass (g)
Tin + Soil			
Soil, m_d			

Water content of soil

At ____ kPa Water Content (%)	At ____ kPa Water Content (%)	At ____ kPa Water Content (%)

APPENDIX E

FREDLUND SWC-150 LABORATORY MANUAL

SWC-150 Test

INTRODUCTION

The SWC-150 device is a simple testing apparatus that is capable of applying matric suction while following various applied net normal stresses. The device is used to obtain the soil-water characteristic curve (SWCC) for a soil. Unlike the Tempe Cell device (which can only apply suction values up to 100 kPa), it can apply matric suction values up to 1500 kPa (15-Bar). It is also capable of applying a one-dimensional loading to the soil specimen. The use of the SWC-150 testing device will allow for more accurate soil-water characteristic curves since the specimen can be subjected to different suction values without dismantling the cell.

APPARATUS AND SUPPLIES

SWC-150 Equipment (See Figure1)

7. Brass cylinder
8. SWC-150 testing device
9. "O" ring seal
10. Ceramic plate (1 through 15- Bar plate)
11. Porous stones that fit with brass cylinder
12. Flushing device (ball-pump)

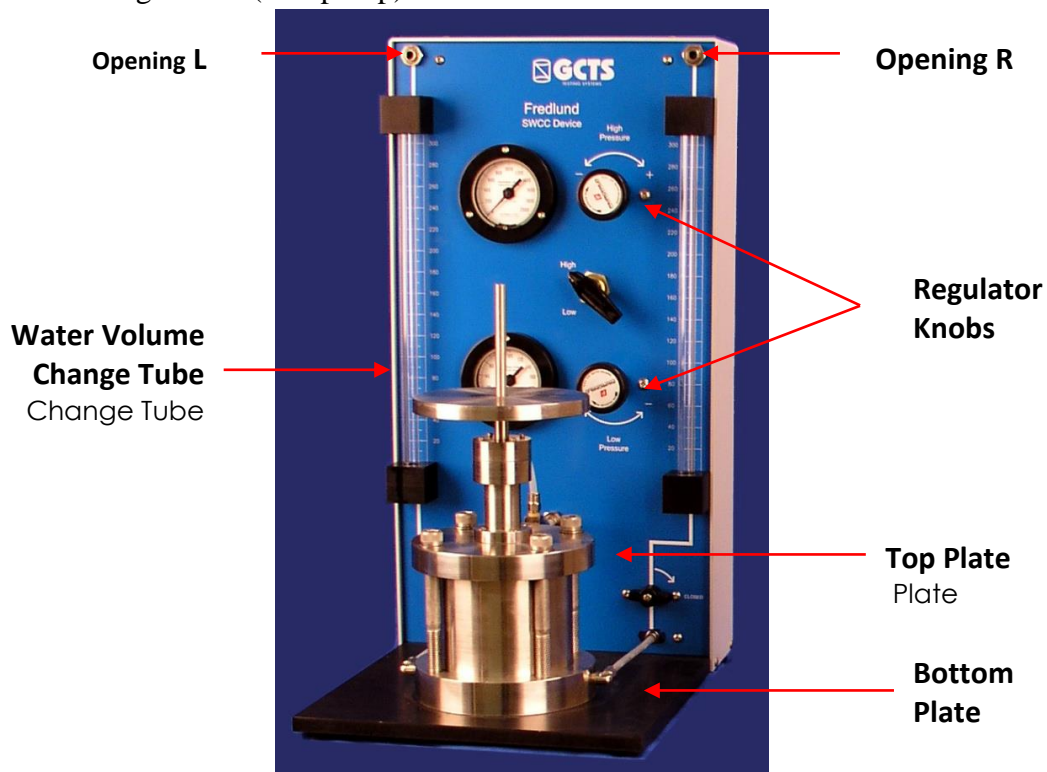


Figure 1: SWC-150 Apparatus

Other Equipment Needed

15. Porous stone
16. Sharp-edge knife
17. Balance
18. Drying oven
19. Spatula
20. Two plastic sandwich bags
21. Air compressor
22. Air pressure inlet tube
23. Containers-handling samples (tin or aluminum moisture cans)
24. Gloves for moving and handling hot containers after drying
25. Scoop
26. Container to saturate the specimen
27. De-aerated water

SAMPLES

3. Soil samples shall be preserved and transported in accordance with ASTM Test Method D 4220 Groups B, C, or D Soils. Keep the samples that are stored prior to testing in non-corrodible airtight containers at a temperature between approximately 3°C and 30°C and in an area that prevents direct contact with sunlight. Disturbed samples in jars or other containers shall be stored in such a way as to reduce moisture condensation on the insides of the containers.
4. The water content determination should be done as soon as practical after sampling, especially if potentially corrodible containers (such as thin-walled steel tubes, paint cans, etc.) or plastic sample bags are used.

SOIL TYPE RECOMMENDATION

Using a certain soil for students to use is crucial in conducting a proper laboratory test for unsaturated soils. The following table shows the characteristics of the soil recommended for the students to use. These soil properties were determined for reasonable equilibrium times and ease of use.

Table 1: Optimum Soil Properties for Use by Students

Soil Type	Gradation Type	Specific Gravity	Liquid Limit (LL)	Plastic Index (PI)
Silt	Well Graded	2.73	20-28	3-7

SOIL INDEX PROPERTY DETERMINATIONS

The determination of some index properties is an important step prior to the suction test, as they will be needed during the analysis section of the report. The following properties should be determined prior to this test:

5. *Specific Gravity of Solids*- The specific gravity shall be determined in accordance with ASTM Test Method D 854 on the soil being used.
6. *Atterberg Limits*- The liquid limit, plastic limit, and plasticity index shall be determined in accordance with ASTM Test Method D 4318 using the soil being used. Atterberg limits are not required for this test method, but they are necessary for proper soil classification and the estimation of the entire SWCC.
7. *Particle Size Distribution*- The particle size distribution shall be determined in accordance with ASTM Test Method D 422 on the soil being used. Particle size distribution is not required for this test but it is necessary to help with visual inspection of the soil specially if it substantial fraction of coarse-grained material is present. The D_{10} value is of particular interest for the estimation of the entire SWCC.
8. *Standard Modified Proctor Test*- The standard proctor test shall be determined in accordance with ASTM Test Method D 698. The maximum dry unit weight and optimum moisture content are needed if reconstituted specimens are compacted at these conditions.

PROCEDURE

The following procedure will allow for the determination of the suction-water content points at a particular overburden stress.

1. Saturate the high air-entry value ceramic stone with de-aerated water in a stainless steel or plastic container for at least 8 hours before assembling the cell. Make sure to use the correct ceramic stone. Refer to Table 2 as a guide to select the ceramic stone.

Table 2: Selection of Ceramic Stone

Type of Soil	Ceramic Stone Type
Sand	1-Bar
Silty Sand, Clayey Sand	3-Bar
Sandy Silt, Sandy Clay	5-Bar
Clay	15-Bar

2. Homogenize the soil to be tested.
3. Determine the dry density, specific gravity, plastic index, and grain size distribution of the soil.
4. Use soil passing No. 4 sieve for this test.
5. Prepare specimen to the density required by your instructor (example: maximum dry density, in-situ density, or other). Table 3 is a guide to determine the amount of soil needed to prepare the specimen.

Table 3: Calculation of dry mass of soil required for the ring

Calculation	SYMBOL	Formula	Remarks
Dry density of the soil (g/cm^3)	ρ_d		Should be determined before hand
Volume of brass cylinder ring (cm^3)	V	$V = \frac{\pi * H * D^2}{4}$	H is the height of ring D is the diameter of ring
Dry mass of soil required to fill the ring (g)	M	$M = \rho_d * V$	V is the volume of ring ρ_d is the dry density

6. Place a filter paper on top of a porous stone.
7. Place the brass cylinder on top of the filter paper.
8. Compact the soil in the ring in two 1.3-cm lifts. Compact the soil with a compaction hammer, about 10 times each lift depending upon the composition of the soil.
9. Once the soil is compacted into the brass cylinder remove excess soil from the top of the cylinder with a spatula and make sure it is leveled out.
10. Place another filter paper on top of the brass cylinder filled with the soil.
11. Place another porous plate on top of the newly placed filter paper.
12. Take the whole sample and place in a deep pan to where the water level is at around $\frac{2}{3}$ the height of the brass ring. This allows the soil specimen to saturate from the bottom up. Do not completely submerge the soil specimen since this might entrap air in the soil.
13. Place a small weight on the top of the soil specimen during the saturation process to prevent swelling.
14. Allow soil to soak the water until saturation is achieved. For sandy soil, it will take approximately 24 hours. For a clayey material, allow to soak water for at least 3 to 4 days.
15. After the sample has been saturated, remove all the assemblage from the pan.
16. If the soil has expanded during the saturation process, trim the top prior to testing.
17. Select a dry glass plate (approximately 10cm x 10cm) and record its weight.
18. Place the saturated specimen on the glass plate without the porous stone and filter papers.
19. Allow the soil specimen to drain any excess water onto the glass plate. The excess water can be removed by mopping it with a paper towel.
20. Dry any water from the glass plate and the outside of the ring.
21. Weigh and record the soil specimen and glass plate.
22. Remove the saturated ceramic stone from the container.
23. Dry the ring around the ceramic stone and lightly mop the top and bottom of the ceramic disk to remove excess water while achieving saturated surface dry condition.
24. Weigh the ceramic disk.

25. Transfer the soil specimen onto the ceramic stone. Make sure the soil specimen is centered in the middle of the stone.
26. Weigh the ceramic stone and the soil.
27. Prepare the SWCC cell assembly by cleaning the O-rings and surfaces. It is important that these surfaces are free from any grits of any impurities.
28. Add some water into the bottom of the plate of the cell.
29. Moisten the outside of the ceramic stone ring by mopping a moist paper towel.
30. Open the valves at the bottom of each water volume change tube and the bottom plate.
31. Carefully press the ceramic stone and the soil specimen into the recess in the bottom plate. Water will rise in the water volume change tubes while performing this step.
32. Place a porous stone on top of the soil specimen.
33. Place the cell wall on the base ensuring the cell wall is placed properly within its O-ring to prevent air leakage.
34. Secure the top plate to the bottom plate by tightening the four 4.5-inch long socket-head cap screws that seal the cell walls.
35. Fill the left volume tube with de-aerated water through the opening located on the top left hand corner of the panel (Opening **L** on Figure 1). Water will flow into the right volume tube pushing some of the trapped air in the base. Stop filling when the tubes are about half full.
36. Use the flushing device (ball-pump) to expel any remaining trapped air in the base. Insert the tip of the ball pump into Opening **L** and squeeze the pump. Be careful not to push the water column into the base plate or spill water from the opening located on the top right water column (Opening **R** on Figure 1). Repeat the flushing process changing water columns until no air bubbles appear during flushing.
37. The water columns should level out in both tubes within a few minutes. Record the two initial volume tube readings along with the date and time. If necessary, more water can be added to bring the water level higher.
38. Apply the desired pressure by selecting either the low or high pressure gauge with the HIGH/LOW valve on the center of the panel.
39. Apply the desired pressure corresponding regulator knob to apply the pressure in the cell.
40. Put additional weights on the weight plate to simulate 4 psi (about 28 kPa). This should simulate the net normal stress or overburden pressure to the specimen.
41. Check the system for any air leaks. This can be done by using a mixture of soapy water. If there are any leaks re-assemble the unit and repeat the process over.
42. Leave the system to equilibrate. Take water volume change readings until you see no further change. Note: it may take 24 hours and up to 3 days to equilibrate.
43. Take final volume change reading once it has equilibrated.
44. Use flushing device to expel any trapped air before applying next pressure increment.
45. Repeat the same procedure for the remainder of the pressure increments.
46. After the last pressure increment, record the volume change readings.

47. Remove the weights on the weight plate.
48. Turn the pressure gauges off or set to zero before disassembling the apparatus.
49. Take the soil specimen out of the cell.
50. Weigh and record the moist specimen.
51. Place the specimen in the oven for at least 24 hours.
52. Take the specimen out of the oven and weigh and record the dry mass of the specimen.

CALIBRATION OF WATER VOLUME CHANGE TUBES

The measurements obtained from the water volume change tubes represent a linear measurement in millimeters. These linear measurements should be converted to a gravimetric calibration factor, α , which can be determined as follows:

1. Fill one of the water volume change tubes with water with closed bottom valve. Record the water volume tube reading, X_1 .
2. Drain about 100 mm of water from the volume tube into a container by opening the bottom valve. Again, record the water volume tube reading, X_2 .
3. Weigh the collected water in grams, W .
4. Calculate the calibration factor, α , as follows $\alpha = W / (X_1 - X_2)$
5. Use α to calculate the amount of water released or absorbed during the SWCC tests. For example, if the difference between the initial and final volume tube readings in a particular test is ΔX , the corresponding weight of water in grams is $(\Delta X) \times (\alpha)$

Soils Testing Laboratory
SWC-150

Location _____

Tested By _____

Type of Soil _____

Ceramic Stone Type _____

Suction Values _____

Table 1: Properties of soil Needed

Calculation	Value Determined
Specific Gravity of soil solids, G_s	
Percent passing #200 sieve, w	
Diameter of soil particle at 10% passing, D_{10}	

Table 2: Dimensions of Brass Ring

	Height of Ring H (cm)	Diameter of Ring D (cm)	Volume of Ring V (cm ³)
1			-----
2			-----
3			-----
Average Dimension			

Volume Equation:

$$V = \frac{H * \pi * D^2}{4}$$

Initial water content determination:

Table 3: Soil before soil is dried in the oven

	Initial Mass (g)
Tin Can	
Tin + Soil,	
Soil, m_w	

Table 4: Soil after soil is dried in the oven

	Initial Mass (g)
Tin + Soil,	
Soil, m_w	

Table 5: Initial water content of soil

Initial Water Content (%)

Water Content Equation:

$$w = \frac{m_{water}}{m_{solids}} * 100\% = \frac{m_w - m_d}{m_d} * 100\%$$

Where

m_w = mass of wet soil

m_d = mass of dry soil

Amount of soil needed for specimen:

Table 6: Amount of soil needed for specimen

Initial water content, w_{initial} (%)	
Optimum water content, w_{opt} (%)	
95% of maximum dry unit weight, $\gamma_{95\% \text{ dry max}}$ (kN/m^3)	
95% of maximum moist unit weight, $\gamma_{95\% \text{ moist max}}$ (kN/m^3)	
Volume of specimen brass ring, V (m^3)	
Moist mass needed for specimen, m (g)	

Maximum moist unit weight calculation:

$$\gamma_{95\% \text{ moist max}} = \gamma_{95\% \text{ dry max}} * (1 + w_{\text{opt}})$$

Moist mass needed calculation:

$$m = \frac{\gamma_{95\% \text{ moist max}} * V}{g}$$

Where

$$\begin{aligned} \gamma_{95\% \text{ dry max}} &= 95\% \text{ of maximum dry unit weight} \\ \gamma_{95\% \text{ moist max}} &= 95\% \text{ of maximum moist unit weight} \\ w_{\text{opt}} &= \text{optimum water content (as a decimal)} \\ m &= \text{mass of soil inside cylinder} \\ V &= \text{volume of brass cylinder} \\ g &= \text{gravity} \end{aligned}$$

Table 7: Calculation of Dry Mass of Soil Required for the Ring

Calculation	<i>Sym bol</i>	Formula	Value Determined	Remarks
Dry density of the soil (g/cm^3)	γ_d			Should be determined before hand
Volume of brass cylinder ring (cm^3)	V	$V = \frac{\pi * H * D^2}{4}$		H is the height of ring D is the diameter of ring
Dry mass of soil required to fill the ring (g)	M	$M = \gamma_d * V * 9.81$		V is the volume of ring γ_d is the dry density

Table 8: Soil Specimen Data before Test

	Mass
Mass of ring	
Mass of glass plate	
Mass of glass plate + saturated specimen	
Mass of saturated ceramic stone	
Mass of saturated ceramic stone + specimen	
Mass of specimen	

Table 9: Soil Specimen Data after Test

	Mass
Mass of ring (g)	
Mass of pan (g)	
Mass of saturated ceramic stone (g)	
Mass of wet specimen + pan (g)	
Mass of wet soil (g)	
Mass of dry specimen + pan (g)	
Mass of dry soil (g)	
Mass of water (g)	
Final Water Content (%)	
Final Degree of Saturation (%)	

Table 10: SWCC Test Data

Date	Time	Matric Suction (<i>kPa</i>)	Volume Reading		Height (<i>mm</i>)

Table 11: Soil Properties at Saturation

Initial Amount of Water Absorbed (<i>g</i>)	Initial Water Content (%)	Initial Dry Density (<i>g/cm</i> ³)	Initial Degree of Saturation (%)

Table 12: Calculation Sheet for Degree of Saturation, S

Matric Suction (<i>kPa</i>)	Water Released (<i>g</i>)	Water Released from Ceramic Stone (<i>g</i>)	Water Content (%)	Specimen Height (<i>mm</i>)	Specimen Volume (<i>cm</i> ³)	Dry Density (<i>g/cm</i> ³)	Degree of Saturation (%)

APPENDIX F

ANALYSIS GUIDE USING THE FREDLUND AND XING (1994) EQUATION

Analysis

The students will be required to construct a soil-water characteristic curve (SWCC) using the Tempe Cell Experiment. They will be required to use Microsoft Excel to do the analysis. Students will be using the Fredlund and Xing equations to construct the SWCC curves.

1. Calculate the water content of soil after testing and calculate the water content at 100% saturation. Water content at 100% saturation can be calculated by saturating a sample and then determining its water content.
2. Calculate the volume of the brass cylinder.
3. Determine the density, dry density, unit weight, and dry unit weight of your soil.
4. Calculate degree of saturation and volumetric water content using the following equations:

Degree of Saturation (in %):

$$S = \frac{w * G_s}{\left(\frac{G_s * \gamma_w}{\gamma_d} - 1\right)}$$

Volumetric Water Content (in decimal):

$$\theta = \frac{w * \gamma_d}{(\gamma_w * 100)}$$

Where,

w = water content (as a decimal)
 G_s = specific gravity of soil solids
 γ_d = dry unit weight of the soil
 γ_w = unit weight of water (use correct units)
 S = degree of saturation (in percentage)
 θ = volumetric water content (in decimal)

5. In excel, create the following columns: matric suction, volumetric water content (%), y_{hat} (%), and constraints.
6. Input your lab data for matric suction with its associated volumetric water content but leave the y_{hat} and constraints cells blank.
7. Make a column for the Fredlund & Xing parameters and leave the cells blank.
8. Under the Fredlund & Xing parameters, add a cell for the sum of square errors.
9. In the constraints cells, input the following formula:

$$\theta - \theta_s * \left[\frac{\left[1 - \frac{\left[\ln \left(\frac{1 + u_a}{h_r} \right) \right]}{\left[\ln \left(\frac{1,000,000}{h_r} \right) \right]} \right]}{\left[\ln \left(e + \frac{u_a}{a} \right)^n \right]^m} \right]$$

Where,

u_a = matric suction
 θ = volumetric water content at any soil suction
 θ_s = saturated volumetric water content at any soil suction
 a, n, m = three soil fitting parameters
 e = void ratio (by using equation $Se = G_s w$)
 w = water content (as a decimal)

10. For sum of square error, input the following formula:

$$= \text{SUMXMY2}(y_{\text{hat}} \text{ column}, \text{volumetric water content column})$$

11. Use solver under the data tab. If you do not have it in your version of Excel, then you will have to download it onto your Excel program. Using the solver function, perform the following steps:
 - a. Click “solver”
 - b. target cell: sum of square error cell
 - c. Equal to: min ---> of: 0
 - d. By changing cells: whole y_{hat} column, all of the Fredlung & Xing parameters cells
 - e. Subject to the constraints: the whole constraints column=0
 - f. Click “solve”
12. If a solution is found, click “ok,” but if not, click “ok” but also check the parameters to make sure they make sense. If you notice any negative numbers, go into solver and add additional constraints since these parameters need to be greater than zero. You may need to play around with solver until it finds a solution.
13. Set up two columns for expected values that will be generated from the previous steps--one for matric suction and another for the water content.
 - a. Make sure you start with 0.001 and include about 40 to 50 different soil suction values between 0.001 to 1,000,000 that way you get a nice long curve

14. In the water content cells, input the following formula:

$$= \theta_s * \left[\frac{\left[1 - \frac{\left[\ln \left(\frac{1 + u_a}{h_r} \right) \right]}{\left[\ln \left(\frac{1,000,000}{h_r} \right) \right]} \right]}{\left[\ln \left(e + \frac{u_a}{a} \right)^n \right]^m} \right]$$

15. Graph. The first of two graphs will be of volumetric water content vs. matric suction

- a. graph both lab results and expected results
- b. make sure to use log scale for the matric suction axis

16. Graph. The second of the two graphs will Degree of Saturation vs matric suction

- a. make sure to log scale the matric suction axis

The graph should look similar to this:

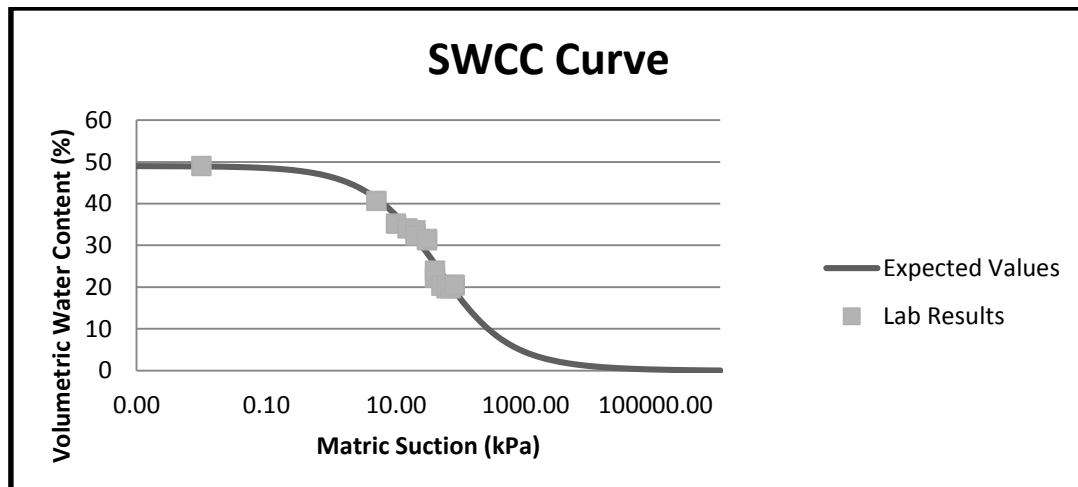


Figure 1: Example of SWCC Graph

Numerical Example

Specimen Data

At beginning of test:

Height of brass cylinder= 30.05 mm

Diameter of brass cylinder= 53.7 mm

$$\text{Volume of brass cylinder} = \frac{\pi * 30.05 * 53.7^2}{4} = 68,058.6 \text{ mm}^3 * \left(\frac{1 \text{ m}}{1000 \text{ mm}}\right)^3 = 6.8 * 10^{-5} \text{ m}^3$$

Mass of porous stone plate= 235.4 g

Mass of filter paper= 1 g

Brass cylinder= 72.7 g

Plate+ filter paper+ brass cylinder + soil= 403.3 g

$$\text{Soil} = 403.3 - 235.4 - 1 - 72.7 = 94.2 \text{ g} * \left(\frac{1 \text{ kg}}{1000 \text{ g}}\right) = 0.0942 \text{ kg}$$

$$\text{Unit weight of soil} = \frac{0.0942 \text{ kg} * 9.81 \frac{\text{m}}{\text{s}^2} * 1 \text{ kN}}{6.8 * 10^{-5} * 1000 \text{ N}} = 13.6 \text{ kN/m}^3$$

Mass of tin can, $M_c = 12.76 \text{ g}$

At end of test:

Mass of entire wet soil plus can, $M_{m+c} = 36.91 \text{ g}$

Mass of entire wet soil, $M_m = 36.91 \text{ g} - 12.76 \text{ g} = 24.15 \text{ g}$

Mass of entire dry soil plus can, $M_{d+c} = 32.40 \text{ g}$

Mass of entire dry soil $M_d = 32.40 \text{ g} - 12.76 \text{ g} = 19.64 \text{ g}$

Mass of water in soil, $M_w = 24.15 \text{ g} - 19.64 \text{ g} = 4.51 \text{ g}$

$$\text{Water Content of soil, } w = \frac{4.51 \text{ g}}{19.64 \text{ g}} * 100\% = 22.96\%$$

Matric Suction vs. Moisture Content

$$\text{Suction, } u_a = 30 \text{ kPa}$$

Analysis

Should be given by instructor or instructor will give information needed to determine the water content at 100% saturation:

$$G_s = 2.73$$

$$\text{Water content at 100\% Saturation} = 49.01\%$$

Degree of Saturation (%):

$$= \frac{22.96 * 2.73}{\left(\frac{2.73 * 9.81 \text{ kN/m}^3}{13.6 \text{ kN/m}^3} - 1 \right)} = 64.67\%$$

Volumetric Water Content (in decimal):

$$= \frac{22.96 * 13.6 \text{ kN/m}^3}{(9.81 \text{ kN/m}^3 * 100)} = 0.3183$$

Then repeat the process two more times at different matric suctions. For simplicity the following two more reading results are:

Run#2:

$$\text{Suction, } u_a = 50 \text{ kPa}$$

$$w = 17.05\%$$

$$\text{Degree of Saturation (\%)} = 46.29\%$$

$$\text{Volumetric } w/c = 0.2321$$

Run#3:

$$\text{Suction, } u_a = 70 \text{ kPa}$$

$$w = 14.52 \%$$

$$\text{Degree of Saturation (\%)} = 39.42\%$$

$$Volumetric\ w/c = 0.1977$$

In excel, create the following columns: matric suction, volumetric water content (%), y_{hat} (%), and constraints.

Input your lab data for matric suction with its associated volumetric water content but leave the y_{hat} and constraints cells blank.

Make a column for the Fredlund & Xing parameters and leave the cells blank.

Under the Fredlund & Xing parameters, add a cell for the sum of square errors.

All the results for this process can be seen in the following tables:

Table 1: Lab Results

Matric Suction (kPa)	Water Content (%)	Dry Density (kN/m³)	Degree of Saturation (%)	Volumetric Water Content
30	22.96	13.6	64.67	0.3183
50	17.05	13.4	46.29	0.2321
70	14.52	13.4	39.42	0.1977

Table 2: Set Up Results in Excel

Matric Suction (kPa)	Vol. w/c (%)	y_{hat} (%)	Constraints	Fredlund & Xing Parameters	
0.01	49.01	48.915975	0.000000000	a	44.301
30	31.26	28.171193	0.000000000	n	0.7401
50	23.21	23.366412	0.000000000	m	2.5329
70	19.77	20.219302	0.000000000	hr	3000
				sum_sq_errors	9.7520

Table 3: Expected Values

Suction (kPa)	Vol. w/c (%)
0.00	49.00706813
0.00	49.00661855
0.00	49.00414686
0.00	48.99056077
0.01	48.9159758
0.02	48.87522606
0.03	48.81632948
0.04	48.73127352
0.07	48.60858249
0.12	48.43190232
0.20	48.17809372
0.33	47.81476383
0.55	47.2972621
0.90	46.56544834
1.48	45.54107696
2.45	44.12764441
4.03	42.21594031
6.65	39.6999396
10.97	36.50714938
18.08	32.64221904
29.81	28.2299482
49.15	23.52912113
81.03	18.8892111
133.60	14.65400781
220.26	11.06123942
363.16	8.19618969
598.74	6.014333924
987.16	4.400321075
1627.55	3.222701453
2683.37	2.365680193
4424.13	1.739692843
7294.16	1.279872271
12026.04	0.94026329
19827.59	0.688169539
32690.17	0.500060788
53896.98	0.358882841

88861.10	0.252256255
1.47E+05	0.17119818
2.42E+05	0.109185809
3.98E+05	0.061468478
6.57E+05	0.024568367
1.00E+06	0

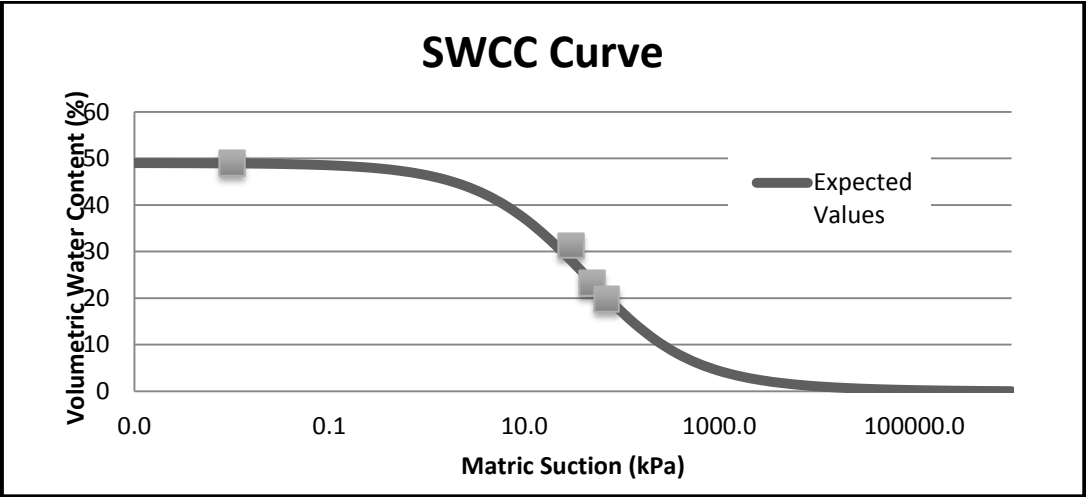


Figure 4: Graph of Example Results

APPENDIX G

ANAYLYSIS GUID USING THE “ONE-POINT” METHOD

ANALYSIS

The students will be required to construct a soil-water characteristic curve (SWCC) using the SWC-150 device. They will be required to use Microsoft Excel to do the analysis. Students then will compare their data points to the family of curves shown in Figure 2 (Zapata 1999, Torres 2011).

1. Calculate the water content of soil after testing and calculate the water content at 100% saturation.
2. Calculate the volume of the brass cylinder.
3. Calculate degree of saturation water content for every pressure increment using the following equation:

$$S = \frac{w * G_s}{\left(\frac{G_s * \gamma_w}{\gamma_d} - 1\right)}$$

Where,

S = Degree of Saturation

w = Water Content

G_s = Specific Gravity of Soil Solids

γ_d = Dry Unit Weight

γ_w = Unit Weight of Water

4. Plot on a graph Degree of Saturation vs. log Matric Suction.
5. Compare data points to the graph in figure 2 to determine the slope of the SWCC using the one-point method. If the soil is granular and non-plastic, then use the diameter of the soil particle, D_{10} , which corresponds to 10% passing from the grain distribution curve. If the soil has some plasticity ($PI > 0$), then you would use the wPI lines. To calculate the wPI, the following equation is used:

$$wPI = \frac{\% \text{ Passing \#200 sieve} * PI}{100}$$

Where, PI is the plastic index of the soil.

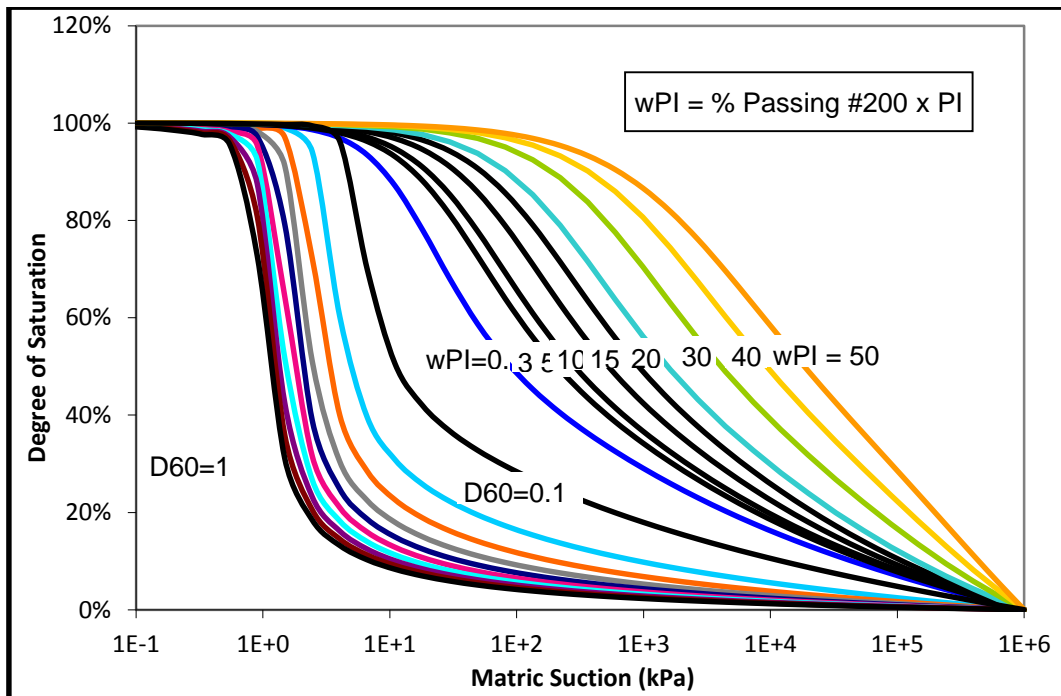


Figure 2: Graph of SWCC of Granular and Plastic Soils (Zapata et al., 2000)